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Watershed-Based Water Quality Management

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WATERSHED-BASED WATER QUALITY MANAGEMENT

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ABSTRACT

WATERSHED-BASED WATER QUALITY MANAGEMENT

by Benjamin Barnett Witherell

In response to landscape alteration and increased knowledge of environmental systems, government regulation for the protection of water quality has undergone several adaptations since the landmark Clean Water Act of 1972. Most recently, in 2000, USEPA moved its emphasis from an effluent-based approach to an ambient or watershed-based approach. Prior watershed studies have uncovered relationships between the type of land cover in a watershed and water quality. These studies have generally indicated correlations between urbanized watersheds and degradation of water quality and aquatic ecosystem health. This dissertation is both an extension of these previous studies to the area of water resource policy and regulation, and it is also a re-examination of the land use/land cover-water quality nexus in light of new high resolution landscape mapping for New Jersey based on recently collected aerial color-infrared orthophotography. Information and data for three watershed management areas (WMA) 1, 6, and 17 used for this study were extracted from high resolution land use mapping for 935 subwatershed assessment units in New Jersey and benthic macroinvertebrate sampling results for 775 sites across New Jersey are used to test the hypothesis that water quality assessment and management using a watershed approach is scale dependent. Statistical analysis indicates that water quality measured using a subwatershed assessment unit correlates to large scale land use patterns, but does not explain the variation of water quality with local land use/land cover. Results indicate that the application of spatial analysis techniques can

inform the relationship between land use metrics and surface water quality impacts. Additionally, two case studies are examined using the relationships and metrics described above. The first case study provides an analysis of adaptive management for water quality restoration activities. The second case study indicates that recent regulatory changes in New Jersey to limit sewer service areas may be overly broad to ensure effective water quality improvement.

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The support and love of my family sustains me always. I am so incredibly lucky to be a part of their lives.

DEDICATION

To my children, Noah and Emily, without you there would be no light.

To my wife, Haekyoung, who is always there for me.

For my parents, Jill and Maynard, I could not have asked for two finer people to follow through life.

For my brother Jake, and his family, your love and support is cherished.

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DISCLAIMERS

Any and all errors or omissions in this dissertation are solely the responsibility of the author.

All basemaps and geographic information system digital data (GIS), unless otherwise noted were obtained from the public website of the New Jersey Department of Environmental Protection (NJDEP). As such, the following disclaimer required of all users of GIS data from the NJDEP applies:

> **This document was developed using New Jersey Department of Environmental Protection Geographic Information System digital data, but this secondary product has not been verified by NJDEP and is not state-authorized.**

Table of Contents

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS/ABBREVIATIONS (as necessary)

ac.	acre
AMNET	Ambient Biomonitoring Network
B-IBI	benthic macroinvertebrate index of biological integrity
CPMI	Coastal Plain Macroinvertebrate Index
CWA	Clean Water Act
GIS	geographic information systems
HGMI	High Gradient Macroinvertebrate Index
HUC11	11-digit hydrologic unit code drainage area
HUC14	14-digit hydrologic unit code drainage area
LULC	Land use and land cover
NGO	Non-governmental organization
NJDEP	New Jersey Department of Environmental Protection
PMI	Pinelands Macroinvertebrate Index
sq km	square kilometer (also km^2)
TMDL	total maximum daily load
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
WMA	watershed management area

Chapter 1 Introduction

1.1 Background

Clean, usable water is integral to a healthy and sustainable society and ecosystem. Stemming from the ability of natural waterbodies to dilute and attenuate waste, and as a result of being a shared common resource, streams and rivers have been used for waste disposal by humanity for millennia (Hardin 1968, Veissman Jr. and Hammer 1985), but the density of development and population increase in the nineteenth and twentieth centuries outpaced the assimilative capacity of many waterways (Hardin 1968, Hines 1966). For much of the twentieth century, water resource management was reactive not proactive (Gleick 2003) and focused on maintaining navigable waterways.

Acknowledging that many rivers, streams, canals and lakes had become unsuitable for anything beyond industrial uses, and that mostly for discharge of waste, the United States Congress passed major amendments to the Federal Water Pollution Control Act (33 USC 1251 et seq.), in 1972. After these significant amendments in 1972, the statute has been known commonly as the Clean Water Act. At that time and since, the United States Environmental Protection Agency (USEPA) has had a mandate to regulate and enforce the provisions of the Clean Water Act (CWA). Acknowledging that water quality improvement and preservation is critical for the protection of public health and the environment, a primary goal of the CWA is to achieve nationally, "water quality which provides for the protection and propagation of fish, shellfish, and wildlife and provides for recreation in and on the water." These provisions are often referred to as waters that are *fishable and swimmable*. The CWA was considered by many to be the most sweeping and productive example of environmental legislation passed by the United States Congress (McThenia, Jr. 1973). Its historical significance is perhaps enhanced by the near unanimous passage, over a Presidential veto, by the 92d Congress.

In 1977, under pressure from USEPA and the public (Goldfarb 1976), the State Legislature of New Jersey passed the Water Quality Planning Act (NJSA 58:11A-1 et seq.) and the Water Pollution Control Act (NJSA 58:10A-1 et seq.) aimed at restoring, maintaining, and preserving "the quality of the waters of the State for the protection and preservation of public health and welfare, food supplies, public water supplies, propagation of fish and wildlife..." These laws were meant to satisfy the requirements of Sections 201, 208 and 303(e) of the CWA to create comprehensive state-level frameworks for water quality protection and improvement. Though not explicitly required by these New Jersey laws, other sections of the CWA do require monitoring and assessment of the State's waters to inform the planning process. Figure 1-1 provides a locational reference for the State of New Jersey.

An effective strategy for managing water resources must include adequate assessment of current conditions, followed by regular monitoring and reassessment. In the 1990s, the USEPA began delegating authority for monitoring and assessment of intrastate waterbodies to the respective individual states. This included information regarding whether waterbodies were meeting their designated uses, as defined by water quality standards (WQS). The requirements from the CWA to accomplish monitoring and assessment of US waters are structurally contained in the Water Quality Inventory

Report (Section 305(b)) and the Impaired Waterbodies List (Section 303(d)) sections of the Clean Water Act. The 303(d) and 305(b) reports had been considered separate tasks and deliverables for many years, but beginning in 2002, the USEPA required states to submit an Integrated Water Quality and Monitoring Report which would include both the Water Quality Inventory report and the Section 303(d) list of impaired waters, along with other relevant information including plans to improve the monitoring and assessment capability and data quality. A typical Integrated Report on water quality monitoring and assessment (see for example, NJDEP 2006a, 2009, 2012) contains information on the following:

- Delineation of water quality assessment units, providing geographic display of assessment results;
- Methods used to assess Designated Use attainment status;
- Designated Use status (attaining WQS, not attaining standard, or insufficient data);
- Management strategies (including Total Maximum Daily Loads (TMDLs) under development to attain water quality standards;
- Pollutants and waters requiring TMDLs;
- TMDL development schedules;
- Progress toward achieving comprehensive assessment of all waters;
- Benefit-cost analysis; and
- Additional monitoring needs and schedules.

The results of water quality assessments and the lists of impaired waters included in the biennial Integrated Reports have implications beyond their satisfying a federal regulatory requirement. The determination of a “listing” and therefore the data that underlie and support those lists are used by lawmakers and regulatory agencies to make decisions regarding: land use policy, federal and state funding, and when to amend or create new laws and initiate executive branch rulemaking. The consequences stemming from water quality assessments indicate the need for a different assessment approach using readily available information, which has similar spatial extent to the spatial extent used for assessment, to assess the likelihood of meeting or not meeting designated uses in New Jersey's subwatersheds. Designated uses for water bodies include one or more of the following: drinking water, biological integrity, industrial or agricultural use, recreation, fisheries, and habitat.

In New Jersey, as in the rest of the United States and many other parts of the world, there has been a general improvement in water quality over the past 50 years through the control of point sources of pollution. However, it is estimated that in the United States, there are more than "21,000 river segments, lakes and estuaries" (NRC 2001) that have been identified as violating one or more water quality standards. The high number of impaired waterways is primarily thought to be due to a lack of attention to impacts from nonpoint source pollution (NRC 1999, 2001). The number of waterbodies not attaining their designated use(s) has led the USEPA to require states to be more diligent in monitoring and assessing water quality by using a watershed approach. Although the CWA has always had provisions for watershed-based management, it was a string of lawsuits in the 1990s that pushed USEPA to write rules explicitly requiring states to implement a watershed-based approach (Cooter 2004). Figure 1-2 shows the 970 subwatersheds and identifies the 20 larger watershed management areas of New Jersey. It is clear from Figure 1-2 that smaller watersheds nest inside larger watersheds and eventually inside major river basins.

USEPA promulgated rules in 2000 that required states to implement stricter monitoring and assessment of their waters, but also required states to create and implement TMDLs to address waters not attaining their designated use, that is impaired. The TMDL approach requires states to calculate waste load allocations (WLA) for point sources and load allocations (LA) for nonpoint sources for any and all water bodies that require a TMDL.

After more than ten years, the USEPA has not adapted the TMDL program substantially. Karr and Yoder (2004) pointed out a "flaw" in the TMDL process, also recognized by the Government Accounting Office (GAO 2004a), that most TMDLs and the assessment process rely on a very small number of parameters, typically five to eight, to assess 5 or more designated uses across many waterbodies in disparate environments.

Some reasons to reconsider current approaches to water resource assessment and management are: 1) many watersheds experience significant contributions of nonpoint source pollution; 2) global climate change, which may have profound impacts on regional and local air temperatures and precipitation patterns that directly influence production of nonpoint source pollution through changes in runoff patterns and magnitude, and atmospheric deposition of pollutants; and 3) rapidly changing land use (from urban decay to suburban and exurban sprawl in western countries and urban growth in many developing areas of the world). Although the effects of climate change on water quality may turn out to be significant, it is not the focus of this dissertation. Whereas, the role of nonpoint pollution and the impact of land use and land cover on water quality is analyzed in this work

1.2 Research objectives

The first objective of this study was to develop an empirical study to introduce and test two new metrics that relate landscape patterns of urban development and agricultural land use to water quality. Landscape dominance, a categorical indicator of the dominant land use/land cover (LULC) in a watershed, was hypothesized to be a predictor of the likelihood that the watershed assessment unit is impaired for one or more designated uses. In this portion of the research, water quality is defined using benthic macroinvertebrate index scores. The second metric introduced here is the urban number, a dimensionless number that combines both the density of urban LULC in a watershed and a measure of the distribution or fragmentation of urban LULC present.

The second objective of this study was to use exploratory spatial data analysis, ESDA, and measures of spatial dependence to test for spatial dependence of land use metrics and water quality measures between and among subwatershed assessment units.

The third objective of the research presented in this dissertation was to apply the results from the first two investigations to two case studies. These case studies provide context for the results from the first two sections of the dissertation. The first case study looked at the case for adaptive watershed management through stream restoration and alternative sampling strategies. The second case study examined the case for water quality planning through land use restriction.

The relevant context and theme of this dissertation research is an analysis of watershed management through government regulation. In most states, including New Jersey, the USEPA delegates planning and water quality management to a designated state agency.

A fourth objective sought to extend the value of linear-style studies to the area of systems analysis and the concept of dynamic feedback in real world systems defined by coupled natural-human interactions. Levin (2006) describes both ecological and human systems as "…complex adaptive systems, in which patterns at the macroscopic level emerge from interactions and selection mechanisms mediated at many levels of organization…" A watershed is one of the most dynamic and tightly-coupled human/natural systems, and as such is a prime laboratory for systems analysis.

1.3 Organization of thesis

The research objectives discussed above were completed, and the results and conclusions were organized into the remaining chapters of this dissertation. The chapters are briefly introduced here:

Chapter 2, *Relationship of land use and land cover to data collection in support of water quality standards, monitoring, and assessment*, defines and tests two new metrics to help understand the relationship between land use and water quality. Chapter 2 includes statistical tests of the explanatory power of these variables to describe the link between urban LULC (human system) and water quality in streams and rivers (natural system) across 935 subwatersheds in New Jersey.

Chapter 3, *Spatial data analysis of a watershed-based approach to water quality assessment*, uses GIS-based mapping and analytical tools to further explore the extent of any correlative and predictive relationship between urban LULC and impairment of designated uses of water in those watersheds. The spatial analysis of data presented in Chapter 3 includes exploratory pattern mapping of both land use and water quality and several additional variables that are oft cited predictors of water quality degradation. An analysis and discussion of the spatial dependence statistics, Global Moran's *I* and a local indicator of spatial association (LISA) applied to the watershed data set is also presented in Chapter 3.

Chapter 4, *Stream restoration and regulation of pollutant loading*, explores the application of physical stream restoration to meet TMDL requirements. The Passaic River basin is presented as a case study, and challenges for watershed-based water quality management in urbanized environments are identified.

Chapter 5, *Use of landscape metrics for water quality management planning under the Clean Water Act*, provides an analysis of recent new regulations in New Jersey designed to apply GIS-based landscape mapping to limit the development of sewer service areas (SSAs) in areas with environmentally sensitive land cover. Environmentally sensitive lands include wetlands and mapped habitat for threatened and endangered species.

Chapter 6, *Watersheds as tightly-coupled, dynamic natural-human systems*, is a conceptual treatment of water quality management through the lens of systems thinking. The application of a system dynamics approach is developed as a decision support tool for integrating socioeconomic information and water quality monitoring information for improved and adaptive management of our life-sustaining water resources.

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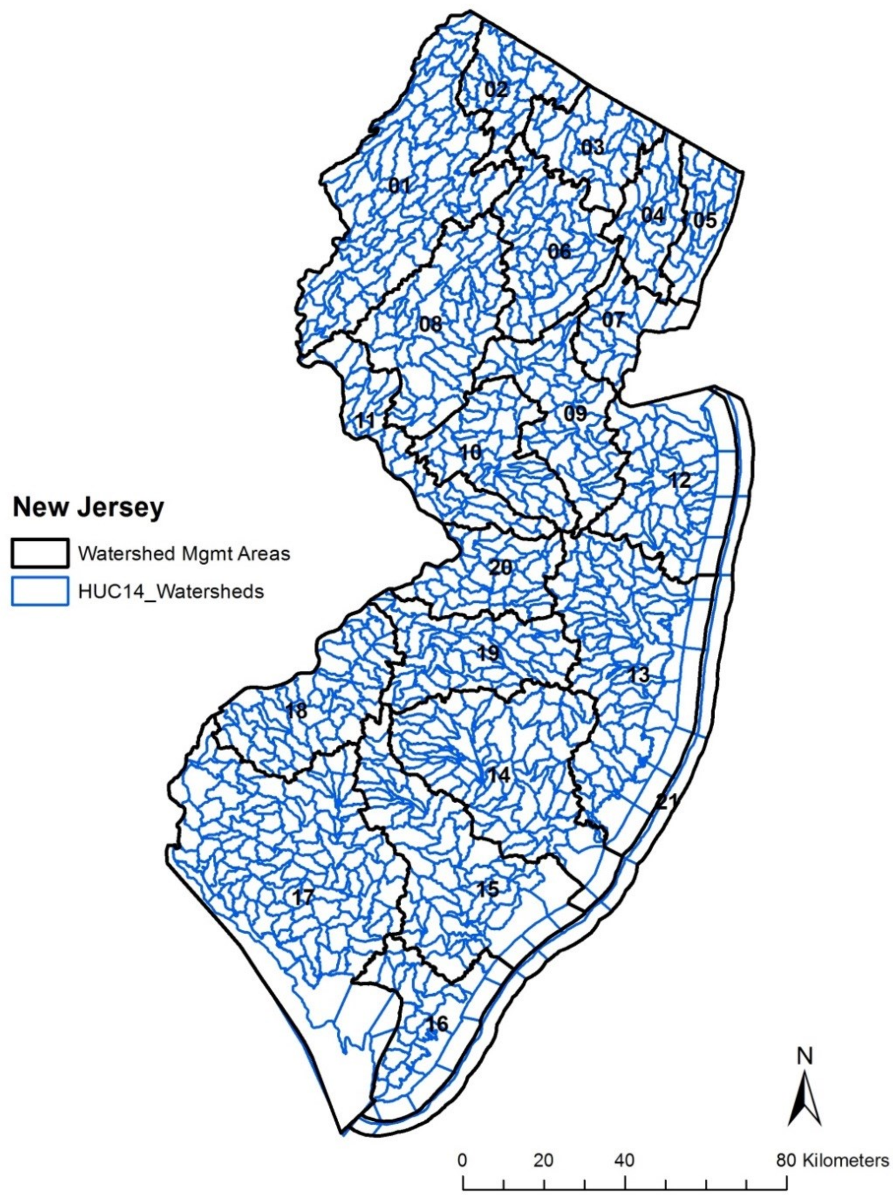
Figure 1-1. State of New Jersey, USA.

Adapted from:
http://education.randmcnally.com/images/edpub/New_Jersey_Counties.png
Last accessed April 2014

Figure 1-2. Subwatersheds and watershed management areas of New Jersey.



Chapter 2 Relationship of land use/land cover and water quality in supporting water quality standards, monitoring, and assessment

Abstract

This study focuses on the assessment of surface water quality under the requirements of the Clean Water Act (CWA) and the influence of land use on whether waterbodies meet water quality standards. The analysis and results presented in this chapter are based on HUC14 subwatersheds statewide and larger Watershed Management Areas (WMAs) 1, 6, and 17, which approximately correspond to HUC11 watersheds. This research uses sample data and results from the NJDEP ambient biomonitoring network (AMNET), which collects and monitors benthic macroinvertebrates from over 750 stations across New Jersey. The work presented here is an extension to the area of water resource policy and regulation of previous studies linking land use/land cover (LULC) to the quality of benthic ecosystems. This study also includes a re-examination of the LULC-water quality nexus in light of new high resolution landscape mapping based on recently captured aerial color-infrared orthophotography made available to the public by the New Jersey Department of Environmental Protection. The results presented indicate that landscapes that are dominated by urban or agricultural LULC are 5-10 times more likely to be associated with impaired water quality than areas not dominated by these LULC types. The findings also suggest that natural land (forest and wetland) dominated areas are approximately 4 times more likely to be watersheds that are attaining their designated use classifications under the Clean Water Act.

2.1 Introduction

When specific water quality characteristics indicate that a waterbody does not meet minimum standards for a designated use, the status for that waterbody under the CWA is considered impaired. Other researchers have previously studied the relationship between land use and land cover (LULC) and the quality of surface waters receiving runoff from the landscape (Booth and Jackson 1997). Utz, Hildebrand and Boward (2009) and Alberti et al. (2007) looked at the impact of urban and impervious surface land covers on aquatic biota in Maryland and Washington State, respectively. Kennen (1998) investigated the connection between aquatic macroinvertebrate populations and landscape and geology in New Jersey. Bockstael (1996), Bolstad and Swank (1997), and Said, Stevens and Sehlke (2004) studied the issue by measuring changes in water chemistry. In an effort to meet the requirements laid out in regulations promulgated by the USEPA, New Jersey collects samples of both benthic biota and water chemistry to support the reporting demands of the CWA.

The analysis presented in this chapter uses data from mesoscale watersheds (HUC11) and subwatersheds in the State of New Jersey, USA. The U.S. Environmental Protection Agency (USEPA) under its authority provided by the CWA directs and oversees states' development of water quality standards intended to protect and allow for designated uses of surface waters. Designated uses for New Jersey waterbodies include:

- aquatic life (including trout production and trout maintenance),
- recreation,
- fish consumption,
- shellfish harvesting for the purpose of consumption,

• drinking water supply,
• industrial water supply, and
• agricultural water supply.

Each of these designated uses has a corresponding set of regulatory-based water quality standards that define the condition of the waterbody necessary to support the designated use. Streams, rivers, lakes, ponds, estuaries, marine waters, and reservoirs are all considered waterbodies to be monitored under the CWA. When the USEPA issues guidance on monitoring and assessment of waterbodies, they may use the term "assessment unit" interchangeably with "waterbody." In 2006, with approval from USEPA, New Jersey changed its assessment unit from waterbody to subwatershed. In New Jersey, assessment units are now 14-digit hydrologic unit code (HUC14) drainage basins. Including coastal waters, there are 970 HUC14 assessment units in New Jersey.

Most states and the EPA employ three main approaches to monitoring environmental conditions of waterbodies:

• fixed-stations,
• probabilistic, and
• targeted.

Each of these methods involves some degree of extrapolation of data from a sampling location to a larger portion of a waterbody. Typically, the area extrapolated to might be one mile upstream and downstream in a river, or to a portion of a lake or estuary. In New Jersey, the NJDEP uses targeted sampling methods to monitor spills and for source identification and tracking. Targeted sampling is typically conducted over short durations at irregular time intervals and not intended to represent ambient conditions.

Probabilistic methodologies result in statistically-derived estimates of water quality and are used exclusively for lakes and estuary waters of New Jersey. Extrapolation of data collected at fixed monitoring locations is the technique used to assess the water quality of New Jersey streams and rivers. A network of these fixed-location monitoring stations exists to assess the overall ambient level of surface water quality in New Jersey. For purposes of managing water resources in New Jersey, the NJDEP has divided the state into 20 watershed management areas (see Figure 2-1), each comprised of many HUC14 subwatersheds.

Based on NJDEP mapping of rivers and streams (1:24,000-scale), there are 18,829 kilometers (km) of non-tidal rivers and streams and 10,336 km of tidal rivers and streams (NJDEP 2006a). The New Jersey stream network, that is the pattern of drainage across the landscape, is shown in Figure 2-2a. For a smaller scale detailed view, see Figure 2-2b, which presents the network of streams draining WMA 1 in northwestern New Jersey. Watershed-based water quality management recognizes that the area of land drained by a stream or river can impact the quality of the water in that stream. In addition to the hydrography, the 20 watershed management areas are comprised of 970 subwatersheds at the 14-digit level hydrologic unit code (HUC14). The HUC14 level is a United States Geological Survey (USGS) designation for the 14 digit hydrologic unit code. Hydrologic unit codes are USGS-designated geographic features that represent watersheds of various nested sizes, a watershed being an area of land whose borders are topographic highs such that all water falling on the land surface drains to a single waterbody or topographic low. In the USGS HUC numbering system, fewer digits indicate relatively larger watersheds, and many digits indicate smaller watersheds. The HUC14 subwatersheds are the smallest watershed unit used by the NJDEP in the assessment of New Jersey waters. The average size of a HUC14 in New Jersey is 2,201 hectares, or about 22 square kilometers (8.5 square miles).

The analysis and results presented in this chapter are based on HUC14 subwatersheds statewide and larger Watershed Management Areas (WMAs) 1, 6, and 17, which approximately correspond to HUC11 watersheds. These three WMAs were chosen for comparison because they represent three distinctly different landscape profiles. Summary information about each WMA is shown in Table 2-1.

Watershed Management Area 6 (WMA 6) is used here to illustrate the data elements used for the analysis presented later in this chapter. WMA 6 covers 935 km^2 of northern New Jersey and includes portions of five counties (Essex, Union, Sussex, Somerset, and Morris) in addition to 52 municipalities. Based on digital maps and 2002 land cover/land use data downloaded from the NJDEP Geographic Information Systems (GIS) website (last accessed 11 March 2014), WMA 6 has 2,285 hectares (2.4%) in agricultural use, 60,883 hectares (65%) in urban lands, and an estimated 20,314 hectares (22%) of impervious surface. Other land covers present in WMA 6 include wetlands and forests, but only urban and agricultural areas are emphasized on the map (Figure 2-3) because these land use/land covers are expected to contribute the greatest negative impact on water quality.

Figure 2-3 shows the spatial extent of agricultural and urban land use in WMA 6, along with the third-order hydrography and the boundaries of the 46 subwatersheds that comprise WMA 6. Land use and land cover (LULC) information was retrieved as LULC layers in ArcGIS shapefile format from the NJDEP GIS download website (http://www.state.nj.us/dep/gis/lists.html). All LULC data used in this dissertation can be found on the State of New Jersey's website as noted above. The two most recent high resolution LULC data sets available from NJDEP GIS are for 2002 and 2007. Table 2-2 shows that the average land use change between 2002 and 2007 across the 935 land based HUC14s was less than one percent for most land use categories and a less than 2% increase in urban land. For the rest of the analyses conducted as part of this research, 2002 LULC was used because other data utilized in this study were collected around the same time period.

2.2 Methods

2.2.1 New Jersey watershed assessment strategies: spatial extent

To illustrate the variation of landscape characteristics among subwatersheds, each subwatershed was mapped to a ternary landscape dominance (L_D) diagram based on the proportion of first-level (NJDEP-modified) Anderson et al. (1976) LULC categories: agricultural, forest, urban, wetland, barren and water. For the purpose of mapping into areas of water-quality-based dominant landscape, and following Utz et al. (2009), forest and wetland areas were combined into one category named "natural." Additionally, most land cover in the "barren" category in the NJDEP land use GIS data results from human disturbance (NJDEP 2014 metadata), and so was added to the "urban" category.

Total land area was normalized by subtracting the amount of "water" area in each subwatershed and then recalculating proportions of the remaining five land cover categories. Figure 2-4 shows the generalized ternary diagram indicating zones of landscape dominance. Figure 2-5a, b, and c illustrate the dominant landscape for each of the subwatersheds in Watershed Management Areas 1, 6, and 17 respectively. In addition, each subwatershed is given a symbol that designates its impairment status as listed in the New Jersey Integrated Water Quality Monitoring and Assessment Report (2006a). The water quality descriptions given in the Integrated Report reflect whether they are attaining water quality standards for a given designated use. The levels are "attaining" (i.e., not impaired), "non-attaining" (impaired), or "insufficient data."

The CWA requires states to report the results of monitoring and assessment conducted at point locations as extrapolated results. The reporting units are typically stream miles for streams and rivers in the inventory section, Section 305(b), of the Integrated Report and discrete waterbodies for the 303(d) section of the Integrated Report. In 2006, the NJDEP changed its definition of assessment unit to maintain a somewhat artificial assessment compliance rate. Prior to 2006 New Jersey, like most other states, used stream order and stream miles to extrapolate results from a monitoring station to a spatial extent measured as stream miles. Between 2004 and 2006, the NJDEP changed the scale of the base resolution of stream coverages from 1:100,000 to 1:24,000. As a result of this change, the number of "mapped" stream miles increased dramatically, and thus the number of unassessed stream miles correspondingly increased. USEPA grades states on the proportion of units assessed, so this mapping unit change for greater resolution may have some unintended consequences.

Anticipating a future increase in base resolution for the stream and river coverage to 1:2,400, and to avoid a large increase in number of unassessed stream miles (even though the ratio to total miles stayed the same), the NJDEP developed a new definition of spatial extent. The new spatial extent for stream assessment units is watershed-based. Results indicating whether or not designated uses are attained at a point monitoring station are extrapolated to the entirety of whatever HUC14 watershed that station falls within. In this way, the attainment or non-attainment of designated uses is extrapolated to all waters within the respective HUC14. The NJDEP considers this new approach to be “more conservative” (i.e., protective) because any impairment as measured by point location analyses will result in a listed impairment for the entire subwatershed. The 970 HUC14 assessment units are presented in Figure 2-6.

Additionally, for each HUC14 with multiple designated use classifications, the most stringent classification will be used for the determination of impairment for the entire HUC14. It is worth noting that the corollary is also true, a result that meets the water quality criteria (no or very low levels of pollution) will generally result in the entire watershed being declared to attain the designated uses for all waters within the watershed. Even with the new watershed-based spatial extent methodology, the NJDEP has assessed all designated uses in only 88 (~10%) of the 970 HUC14 subwatersheds. Full assessment of all designated uses except fish consumption has been achieved in only 241 (~25%) of the assessment units.

Although there are inherent weaknesses (e.g., loss of specification and increasing overall uncertainty, increase of both false negatives and false positives) in extrapolating in-stream point monitoring to an entire subwatershed, several important facts support the change. First, prior research has shown clear connections between human activity, especially conversion of natural land cover to urban and agricultural uses, and resultant impacts to the hydrologic and ecologic systems connected to those land areas (e.g., Alberti et al. 2007, Naiman and Bilby 1998, Bolstad and Swank 1997, Bockstael 1996, Arnold and Gibbons 1996, and Schueler 1994).

Second, the USEPA is moving more toward watershed-based management for water resource protection and restoration, evidenced by funding states for collaborative watershed strategies through the CWA Section 319 grant program (Hardy and Koontz 2008). Third, although aquatic ecosystems and natural hydrologic systems are sentinels in the sense that this is where critical anthropogenic impacts accumulate, watershed lands and land use are where the root causes of those cumulative effects begin. In that way, watersheds are an appropriate geographic unit for integrative management of water resources. Healey (1998) states that "using watersheds for ecosystem management allows for a logical emphasis on the linkages between land and water."

2.2.2 New Jersey watershed assessment strategies: indicators sampling

The NJDEP uses three primary types of stations in its fixed monitoring network:

Ambient Stream Monitoring. A network of over 200 sites is jointly operated by the NJDEP and the USGS, Figure 2-7. According to the 2006 Integrated Report

(NJDEP 2006a), "the chemical/physical networks monitor conventional parameters, metals, bacteria, pesticides, volatile organic compounds (VOC's) and sediments."

Ambient Biological Monitoring Network (AMNET). This network of more than 760 sampling locations throughout New Jersey (NJDEP 2012a) is primarily used for sampling benthic macroinvertebrate assemblages, Figure 2-8. Benthic macroinvertebrate species are considered important indicator species for impact to aquatic ecosystems (Hershey and Lamberti 1998). A subset of these locations is also used for monitoring fin fish populations.

In 2004, NJDEP created three multimetric, regional, genus-level indices of benthic macroinvertebrate integrity. Prior to 2004, samples of benthic macroinvertebrates were scored using a single family-level scoring paradigm. The genus-level regional indices were created to provide greater resolution and detailed information about the health and integrity of the stream ecosystem. The regions where the three indices are used are pictured in Figure 2-9.

Existing Water Quality (EWQ). NJDEP maintains a smaller network of sites to monitor physical and chemical conditions primarily to support antidegradation policies.

In addition to the above monitoring networks, the NJDEP collects data from lake, estuary, coastal, and targeted monitoring efforts. An example of typical monitoring locations in a watershed management area can be seen in Figure-2-10, which shows the locations of primary stream monitoring sites in WMA 6. Given the NJDEP's spatial extent and assessment methodology, it is important to note that some subwatersheds (HUC14s) have more than one monitoring location and others have none. Due to the anisotropy in monitoring density and because the NJDEP uses both numeric and narrative criteria to assess designated uses, the NJDEP has developed a minimum suite of parameters to determine if a designated use is attained or not attained. Table 2-3, adapted from the 2006 Integrated Report (NJDEP 2006a), defines these minimum requirements.

When there are multiple lines of evidence for a particular assessment unit (HUC14), the NJDEP has stated (NJDEP 2006a); the NJDEP weighs the various data available to determine which information is of greatest value, or a combination of data may be used in the final assessment. Figure-2-10 shows that some subwatersheds have more than one station and more than one monitoring type present in or adjacent to the HUC14. NJDEP (2006a) indicates that where a monitoring location is in a stream that forms the boundary between two HUCs, then the data will be assumed to represent both units. While a sampling point may appear to be on the boundary of two watersheds geographically, hydrologically this should be a rare circumstance given the definition of a watershed. Watershed boundaries tend to share topographic high areas like ridgelines, with the streams in the valley or middle of the watershed.

This research examines the potential impact of LULC on water quality using benthic macroinvertebrate data collected from the AMNET stations during Round 3 sampling from 2002 to 2007 (NJDEP 2012a). Based on the extensive coverage of macroinvertebrate sampling sites compared to sites where water chemistry samples are collected, more subwatersheds are assessed using a benthic macroinvertebrate index than any other assessment method. In addition, the location of AMNET monitoring stations provides effective coverage of most of the state's HUC14 watersheds.

The NJDEP developed three different multimetric benthic macroinvertebrate indices for use in three separate physiographic areas of the state (see Figure 2-9 and NJDEP 2012a). The High Gradient Macroinvertebrate Index (HGMI) is for use in fast moving, high-gradient streams and rivers in the northern part of the state. The Pinelands Macroinvertebrate Index (PMI) applies to waterbodies in the Pinelands region of the state. The Coastal Plain Macroinvertebrate Index (CPMI) is used to assess the integrity of benthic communities in streams and rivers flowing through areas of the state with coastal plain physiography.

The three B-IBIs (benthic index of biotic integrity) listed above yield different scores depending on the specific metrics relevant for each index, the details of which are given in the NJDEP reports on macroinvertebrate sampling, and can be found at: http://www.state.nj.us/dep/wms/bfbm/amnet.html (NJDEP 2012a). Although the three indices use different scoring systems for the raw scores, the raw scores are translated into four major categories of condition that are consistent across all sites. Macroinvertebrate index scores are assigned to one of the following categories in increasing order of quality: poor, fair, good and excellent. For the sake of communicating results from freshwater biological monitoring to the public and other interested parties, information about the condition of water and habitat quality at a given location is usually provided using these four categories.

The results of benthic macroinvertebrate sampling are also used to support the regulatory process. In particular the results are used to assess water quality and determine if designated uses for a waterbody or assessment unit are being met, or require remedial action. For regulatory purposes, the four categories listed above are further aggregated into two categories. Under the reporting requirements of Section 303(d) of the CWA, waterbodies are to be listed as attaining or not attaining their designated uses. The four categories that relate HGMI, PMI and CPMI scores to overall water quality are aggregated as follows for compliance with the requirements of Section 303(d): a result of “Poor” or “Fair” indicates the waterbody status is “not attaining” one or more designated uses, and a result of “Good” or “Excellent” indicates that designated uses are being attained at that location.

For subwatersheds with associated AMNET sampling stations, the results of macroinvertebrate sampling were compared to landscape metrics to test for statistically significant relationships. The statistics and results are described in the following sections of this chapter.

2.2.3 Stream Impairment: hypothesis of possible explanatory factors

To test the effectiveness of using subwatersheds as water quality assessment units, new metrics are proposed that can be used as proxies for cumulative effects as measured by biological, physical, or chemical changes in the aquatic environments being assessed. In this research, it is hypothesized that these two new metrics, landscape dominance and urban number can be used to predict the influence of LULC on water quality, as measured by a multimetric benthic macroinvertebrate index of biological integrity or B-IBI.

As discussed previously, many researchers have modeled various watershed characteristics in an effort to relate them to degradation in aquatic ecosystems. Degradation of aquatic ecosystems is the primary cause of waterbodies not meeting their designated use goals and thereby being listed on the 303(d) list (sublists 4 and 5 of the Integrated Report). Schueler (1994) indicated positive correlations between the percent of impervious cover in a watershed or on a site and the amount of runoff, phosphorus loading and stream channel instability, and a negative correlation between percent impervious surface and macroinvertebrate populations. Bolstad and Swank (1997) showed that the cumulative impact of increasing urban and agricultural land use along a downstream gradient resulted in measurable and significant impacts on stream water quality, especially during peak discharge events. Bockstael (1996) showed a strong relationship between nitrogen loading and land use, where residential and agricultural land uses accounted for more than 83% of the nitrogen loading to the Patuxent watershed in eastern Maryland. Lathrop et al. (2007) used an impervious cover threshold of 10% (using HUC11 watersheds) to indicate degradation in watersheds in the New Jersey and New York Highlands.

Additionally, Utz et al. (2009) state that “the broad classes of urban and agriculture are surrogates for the specific mechanisms that cause the loss of sensitive taxa from streams and thus form convenient yet relevant measures for analysis.” With the weight of evidence from these studies and many others that point to a significant and measurable relationship between land use, particularly urban and agricultural, and stream health and aquatic ecosystem integrity, it follows that B-IBI is a valid surrogate for testing the sensitivity of subwatershed assessment units to the impact of land use on water quality.

The quality of water in streams, and hence the ability to meet designated uses in a waterbody, is directly related to the source of the water and what the water comes in contact with prior to it entering the waterbody (Thomann and Mueller 1987, p9). The sources of water entering receiving waters can be summed up by three major categories: direct runoff from the land surface, return flows via point sources of stormwater and wastewater discharge, and groundwater discharge to the waterbody. This study assumes the aggregate effect of these flows in any given location is reflected in the measurement of B-IBI in that same area.

Additionally, this study seeks to test the hypothesis that landscape metrics can be used to estimate the likelihood that a given assessment unit, a HUC14 subwatershed, is impaired. The implications of this study have broad implications for water resources management beyond the specific question of land use impact on water quality at subwatershed and mesowatershed scales. When a waterbody, or assessment unit, is listed on the 303(d) list of impaired waters, the listing often triggers a regulatory response requiring development of a remedial action strategy. The remedial action typically will take one of three forms: 1) development of a total maximum daily load (TMDL), 2) watershed restoration project, or 3) water-quality based effluent limits (WQBEL). These are expensive projects to develop and implement and have long-term planning horizons. The resulting management impact can have significant fiscal and policy consequences.

2.2.4 Subwatershed Impairment: statistical analysis and regression model development

Statistical analysis of the relationship between water quality, as measured by a multimetric macroinvertebrate index of biological integrity, and LULC characteristics were conducted. LULC characteristics analyzed were 1) proportion of Anderson level I LULC, and 2) landscape dominance (L_D), a threshold measure of when a watershed is greater than 50% in agricultural, urban, or natural LULC. L_D is conveniently described on ternary diagrams, such as the ones in Figure 2-5. Both, percent of watershed in specific Anderson Level I LULC and categorical threshold L_D values were determined for subwatersheds that also had associated benthic macroinvertebrate sampling results.

Macroinvertebrate sampling results, from the third round of statewide sampling (2002-2007), were available for 759 AMNET stations. The results are provided in Appendix A. NJDEP divided the state into three separate zones based on physiographic characteristics. Because indices and therefore the scale for raw scores varied across three physiographic areas, analysis was conducted on the categorical results. Odds ratio test, chi-squared test and logistic regression were performed to test for the hypothesized relationship between landscape profiles and water quality based on macroinvertebrate sample data.

Another focus of this research was to examine the potential impact of multiple indicators at the scale of a single watershed management area. Detailed land use data for urban and agricultural land in WMA 6 was compiled from NJDEP GIS coverages and is provided in Table 2-4. As described previously, the LULC data was interpreted by NJDEP from 2002 color infrared imagery with a minimum mapping unit of 1 acre.
A logistic regression analysis was performed to examine the case for a link between regulatory status of impairment for a watershed and the potential explanatory variables of urban land cover, agricultural land cover, and impervious surface cover and number of surface water dischargers in WMA 6. Odds ratios were also calculated for L_D and impairment status in WMA 6.

Because the response variable, impairment status, is a binary or nominal response, a standard linear regression cannot be used. As seen in Table 2-4, the impairment status is 1 if the subwatershed is impaired and 0 if it is not impaired. Figure-2-11 illustrates the locations of subwatersheds with impaired status in WMA 6. Impairment status was considered a 1 if the HUC14 was listed on the 303(d) list (Sublists 4 or 5) of the New Jersey 2006 Integrated Report. Four of the 46 subwatersheds in WMA 6 are on the NJDEP Integrated Report Sublist 3 (insufficient data). For the purpose of this study the four assessment units were removed from the statistical analysis.

Simple linear regression assumes that the response is a linear function of the explanatory variable(s) and that the error structure (how individual measurements vary from the mean or expected value) is normally distributed and has constant variance. Binary responses, values of 0 or 1 for example, can also be thought of as a probability, where the sum of the probabilities for the response being a 1 or a 0 must add to 1. Following Cook et al. (2000), this is expressed as:

$\text{Prob}(Y_i=1) = \pi_i$ (Eq. 2-1)

$\text{Prob}(Y_i=0) = 1 - \pi_i$ (Eq. 2-2)

So generally, $E(Y_i) = 0*(1 - \pi_i) + 1* \pi_i = \pi_i$ (Eq. 2-3)

With an explanatory variable, Eq.1 becomes:

$$E(Y_i|X_i) = \beta_0 + \beta_1 X_i = \pi_i \quad \text{(Eq. 2-4)}$$

Equation 2-2 indicates that π_i is a function of Y_i and so the variance of Y_i is also a function of π_i. Therefore, the assumption of constant variance is violated, and inferences made on binary responses using a simple linear regression would not be valid. With binary response data, the expected response is (the probability of a 1 or a 0) more appropriately modeled as a non-linear relationship (Cook et al. 2000, p.9). Cook suggests binary response data be analyzed with a logit (logistic) transformation and a maximum likelihood estimator.

The logit transforms the non-linear relationship, between the explanatory variable and the probability that the response is one of two outcomes, to a linear one. This transform also keeps the predicted response bounded between 0 and 1. The logit transform is the natural or base-10 log of the ratio of the probability of one outcome to the probability of the other outcome (e.g., ratio of probability of a subwatershed being impaired and the probability that it is not impaired). Based on Equation 2-4, the log transform looks like this:

$$\pi'_i = \ln\left(\frac{\pi_i}{1 - \pi_i}\right) = \beta_0 + \beta_1 X_i \qquad \text{(Eq. 2-5)}$$

Use of the maximum likelihood estimator with the logit transform allows for relaxation of the error structure assumptions that variance be constant and normally distributed. The ability of this approach to be able to assess the fit of the predicted response to observed responses (probabilities) and be able to assess the significance of the estimated parameters (regression coefficients) is useful for analysis of watershed impairment status. This technique has been used for other applications including analysis of variables with strong spatial dependence. Some examples include: prediction of landslide hazards (Ohlmacher and Davis 2003), ecological spatial prediction of wetland plant occurrence (van Horssen et al. 2002), and spatial pattern of farmland in the Maotiao River Basin, China (Huang et al. 2007).

2.3 Results and Discussion

The influence of landscape, especially urban LULC on water quality was examined using several measures, keeping in mind that the regulatory assessment units in New Jersey are HUC14 subwatersheds. Estimates of the overall magnitude of land cover types, such as urban, agricultural and natural, in a subwatershed were calculated from high resolution vector GIS layers. The GIS vector layers were drawn from high resolution color-infrared orthophotography produced by the NJDEP. By using vector data, it is possible to examine and relate individual patches (i.e., GIS polygons) of various land use types to each other and to the watershed as a whole.

For this investigation, multimetric benthic macroinvertebrate index scores were used as a proxy for water quality. In particular, scores from the third round of NJDEP sampling from the state's AMNET biomonitoring stations were used to represent water quality. Previous research (e.g., Utz et al. 2009 and Alberti et al. 2007) showed that B-IBI is a valuable predictor of overall stream quality and in-stream water quality. Earlier investigations (e.g., Kennen 1998) have indicated that B-IBI is especially sensitive to urban runoff.

2.3.1 Chi-square test on contingency tables

SYSTAT (version 12), statistical software package, was used to perform the statistical tests conducted in this investigation. The first hypothesis tested was that L_D has an effect on B-IBI in the watersheds studied. Contingency table analysis was the first test to determine if a relationship was present. The analysis was performed by building contingency tables with L_D categories (Agriculture, Mixed, Natural and Urban) as the rows and B-IBI categories (Excellent, Good, Fair, and Poor) as the columns. The resulting cross tabular cells are the frequencies of the row effect (L_D) and column response (B-IBI) occurring in same subwatershed. The hypothesis was tested using a chi-square test on the resulting contingency table. Table 2-5 provides the results of the chi-square test of contingency for subwatersheds in the coastal plain areas of New Jersey.

The chi-square test on the contingency tables was conducted separately for CPMI and for HGMI areas of the state for two reasons. First, to test if any effect exhibited in one regime and not the other, and secondly because the sample HGMI data set did not contain any subwatersheds with L_D = Agriculture. With no “agricultural” subwatersheds in the HGMI data, the contingency tables were different sizes and therefore a chi-square distribution with different degrees of freedom was required as the underlying distribution for the hypothesis test. The HGMI data forms a 3x4 contingency table, as seen in Table 2-6, and the CPMI data set is analyzed using a 4x4 contingency table. The results show that the effect is statistically significant and the cell frequencies would not have occurred by chance and so an effect of land use on B-IBI is present in these subwatersheds.

However, it is seen that the cell frequencies for L_D = Urban and L_D = Agriculture and B-IBI scores in the “Excellent” and “Good” were very low. Although this was expected and indeed part of the hypothesis, the P-value of the chi-square test is considered unreliable if some cell frequencies are very low, less than five is generally considered too low. Because it cannot be claimed with statistical certainty that the chi-square results are valid, an odds ratio test was performed.

2.3.2 Odds ratio tests

The odds ratio test has several advantages. First it is appropriate for a 2x2 contingency table, so the data was further reduced to test the refined hypothesis that L_D is related to the probability that a water quality assessment unit is impaired. For compliance with USEPA reporting requirements the terms “attaining” and “not attaining” or "non-attaining" are used to indicate impaired or unimpaired status for meeting designated uses in receiving waters. Another advantage of the odds ratio test is that it does not assume an underlying distribution, but instead compares the probability of an event versus the probability of no event. Also advantageous is that the odds ratio is a measure of effect size or strength of the relationship between variables.

The 2x2 contingency tables for odds ratio tests were constructed with L_D = Urban, and L_D = Agriculture as the treatments and "Not attaining" designated use as the event or outcome. Additionally, an odds ratio test result was obtained for L_D = Natural as the treatment and "Attaining" designated use as the event or outcome. Contingency tables and results are provided in Table 2-7. All three tests indicated significance for the hypothesis tested, with P-values =<0.001, with alpha set at 0.05. If the odds ratio is significantly larger than 1, as in all three cases described above, and 1 is not within the 95% confidence interval, then the hypothesis is accepted that L_D increases the probability of the outcome in the expected direction.

The odds ratio test also provides information about the strength of the relationship between the variables. The results summarized in Table 2-7 indicate that among the subwatersheds examined the negative influence of urban dominated landscapes on water quality was strongest. If a subwatershed is dominated by urban LULC, it is 11 times (95% CI = 6.1 to 19.9) more likely than those HUC14s not dominated by urban landscape to be impaired. The negative impact of agricultural dominated areas is shown to be about half that of urban areas in this study, however the number of HUC14s with L_D = Agriculture is only about a quarter the number with L_D = Urban. When L_D = Agriculture, the odds of that subwatershed being impaired increase 5 times (95% CI = 2.1 to 12.3) compared to watersheds not dominated by agricultural landscape. Similarly, the odds that a HUC14 is meeting its designated uses when dominated by natural landscape are 3.9 times higher (95% CI = 2.9 to 5.4) than when $L_D \neq$ Natural.

2.3.3 Logistic regression models

Results of the odds ratio tests provided confidence that a logistic regression could further inform the relationship between B-IBI and LULC. Logistic regression was chosen because the dependent variable, attainment status, is nominal. Also, the form the equation takes, as described earlier in section 2.3.4, is that the dependent variable is the natural log of the odds. The null hypothesis tested that the probability of the nominal dependent variable taking a particular value is <u>not</u> associated with the value of the independent variable. If the null hypothesis is rejected, then a significant relationship exists between the variables.

The same data set of 759 subwatersheds with B-IBI measurements, as a proxy for water quality, and GIS land use data that was used for the odds ratio tests was used for the logistic and multiple logistic regression analysis described in this section. The first regression compared the percent of urban LULC in a subwatershed with the probability that the watershed is impaired. The results, summarized in Table 2-8, indicate that the null hypothesis should be rejected and there is a positive relationship between these two variables. That is, as the amount of urban land use increases, the probability of the subwatershed being impaired also increases.

From the odds ratio tests, it was evident that the L_D = agriculture in a watershed also increases the odds that the watershed will be impaired. The proportion of agriculture LULC was added to the above model and the multiple logistic regression model was calculated. The results in Table 2-9 suggest that the logistic regression model including both percent urban land and percent agricultural land as independent variables is still significant for predicting the probability that a watershed is not attaining the designated uses. However comparison of the goodness of fit statistics for the two models indicates that adding the proportion of agricultural land does not substantially improve the fit of the model to this data set.

2.4 Conclusions

This investigation showed that detailed LULC from high-resolution landscape mapping can be used to estimate dominant LULC in a watershed (L_D) and that L_D is a significant predictor of the likelihood that a watershed is impaired. To estimate water quality impairment status, sampling data and results from the NJDEP ambient biomonitoring network (AMNET) were compiled for more than 750 AMNET stations across New Jersey.

The results presented indicate that landscapes that are dominated by urban or agricultural LULC are 5-10 times more likely to be associated with impaired water quality than areas not dominated by these LULC types. The findings also suggest that natural land (forest and wetland) dominated areas are approximately 4 times more likely to be watersheds that are attaining their designated use classifications under the Clean Water Act.

The influence of the proportion of a watershed in urban or agricultural LULC was modeled using logistic regression to estimate the likelihood that the waterbody is impaired. The models indicate that there is a significant increase in the chance a watershed is impaired as urban land cover and agricultural land use increase.

This study focused on the assessment of surface water quality under the requirements of the Clean Water Act (CWA) and the influence of land use on whether waterbodies meet water quality standards. Landscape dominance, L_D, a categorical metric, is shown to be a reasonable predictor of regulatory impairment status under the Clean Water Act. L_D is defined as a single LULC, such as agriculture or urban or natural lands that cover more than 50 percent of a watershed. As USEPA continues to adopt and adapt to a watershed focus for monitoring and managing water quality, metrics such as L_D can play a role in water resource management. Many government agencies, especially environmental agencies are more budget-constrained each year. Metrics like L_D that are easy to determine and easy to communicate, can be highly useful to environmental managers and regulators. Some important potential applications include: 1) basis for targeted sampling programs, 2) support for land use and water resource protection rulemaking, and 3) support for land preservation activities by non-government organizations (NGOs) or state and local government open space acquisition programs.

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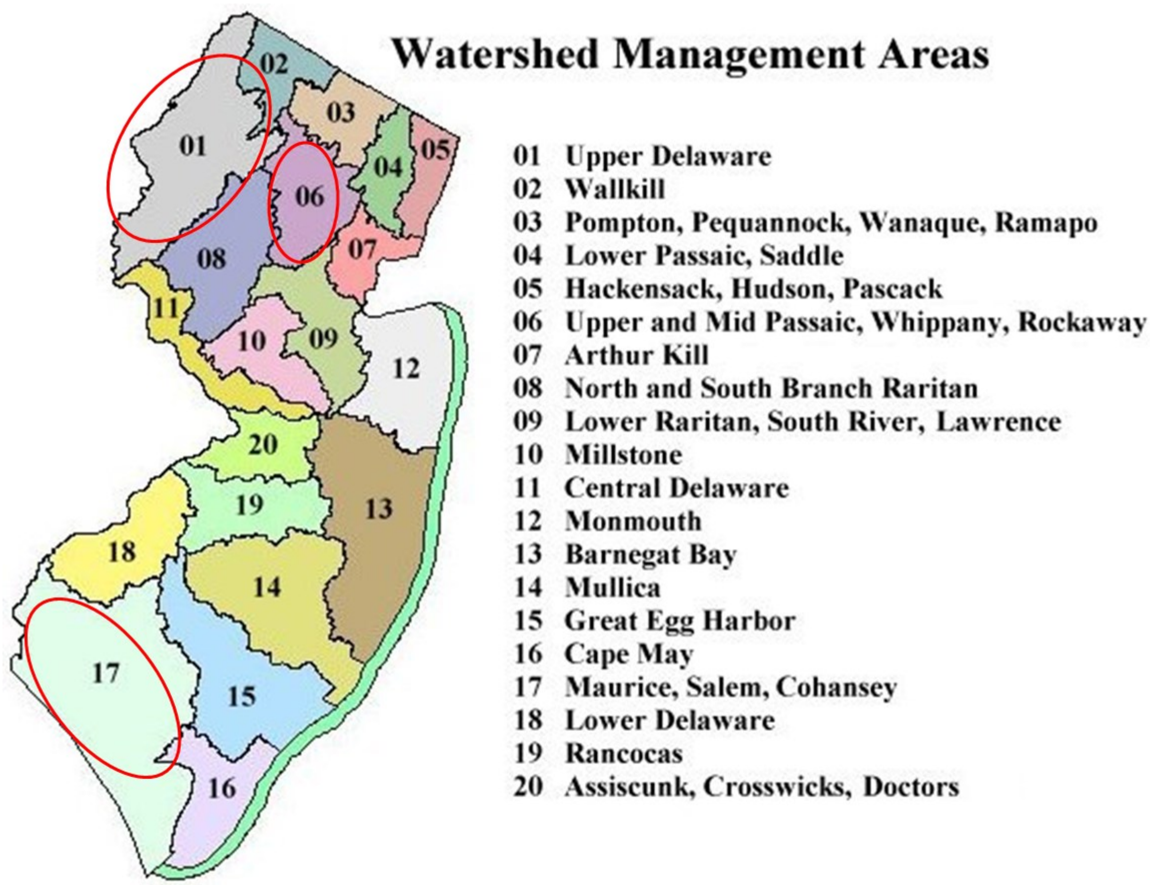
Figure 2-1. Watershed Management Areas of New Jersey.



(base map from NJDEP GIS, website, http://www.state.nj.us/dep/gis/lists.html)

Figure 2-2a. New Jersey streams and rivers.

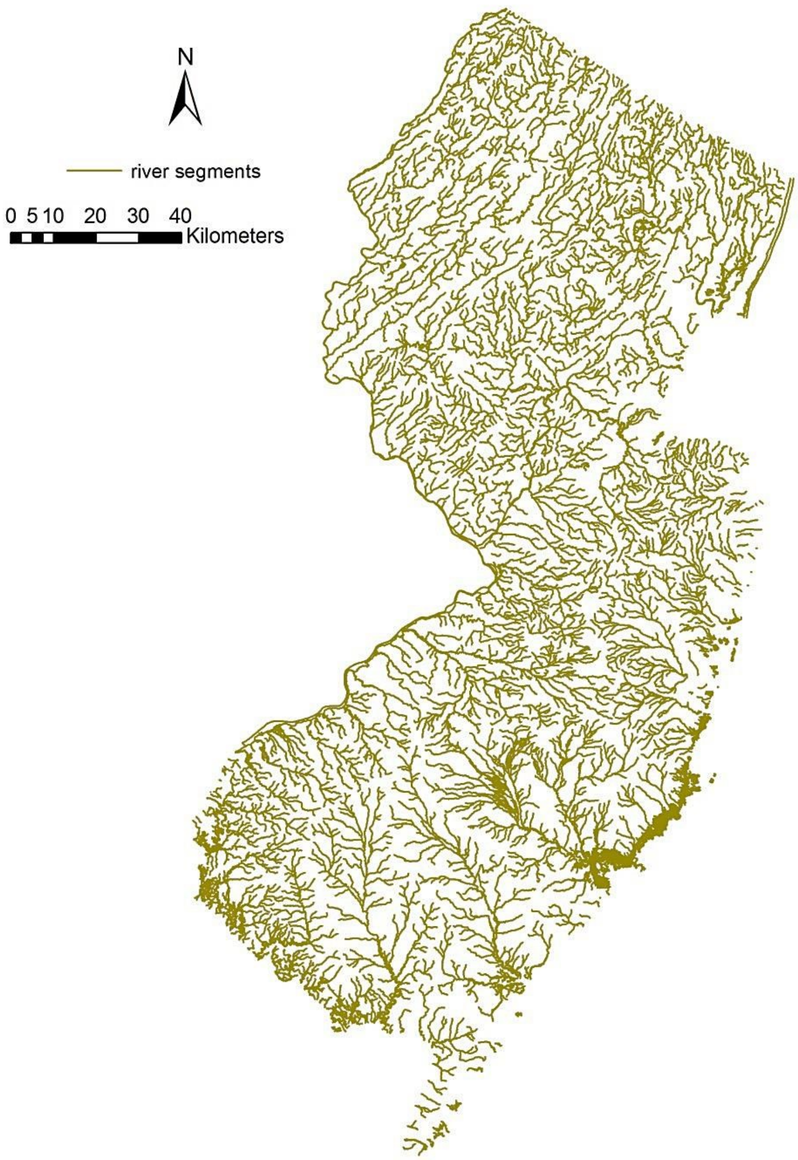


Figure 2-2b. Streams of Watershed Management Area 1

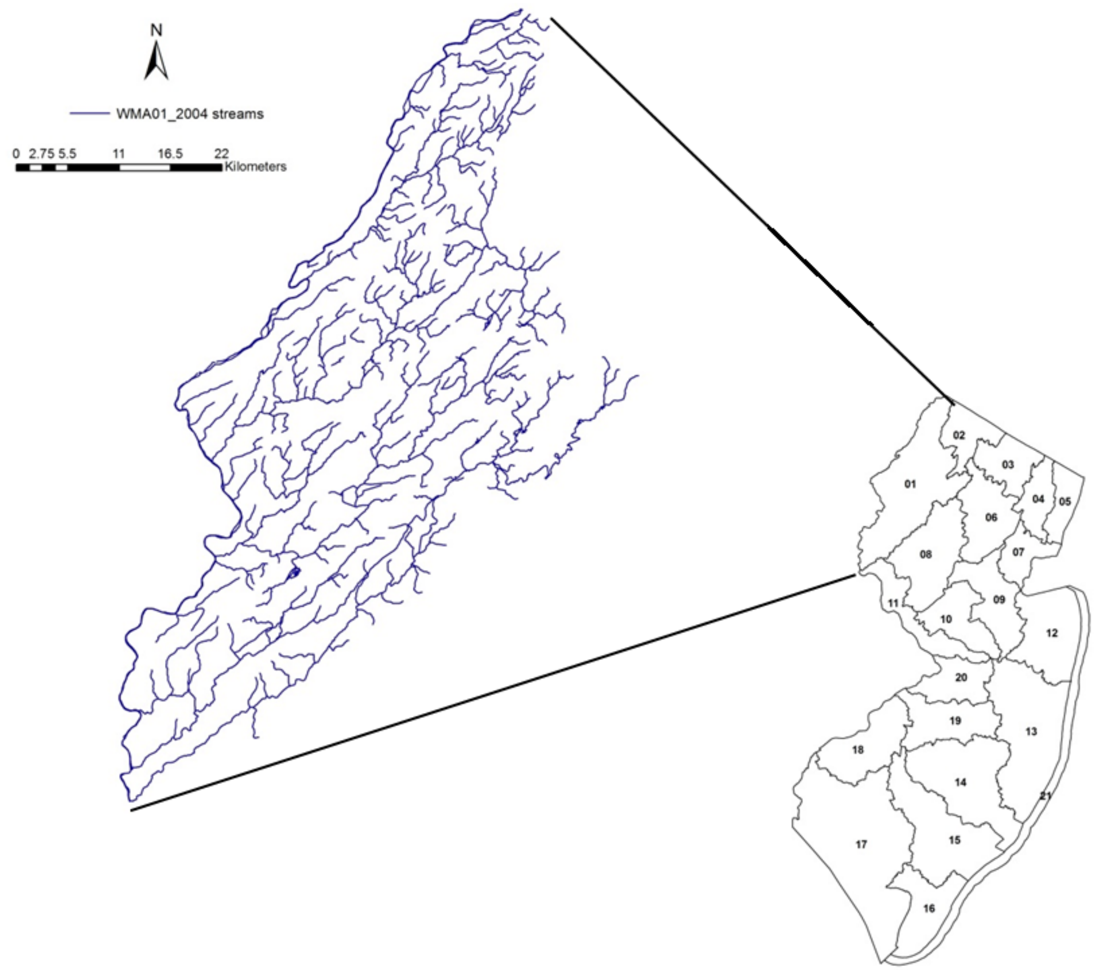


Figure 2-3. Agricultural and urban land use in WMA 6.

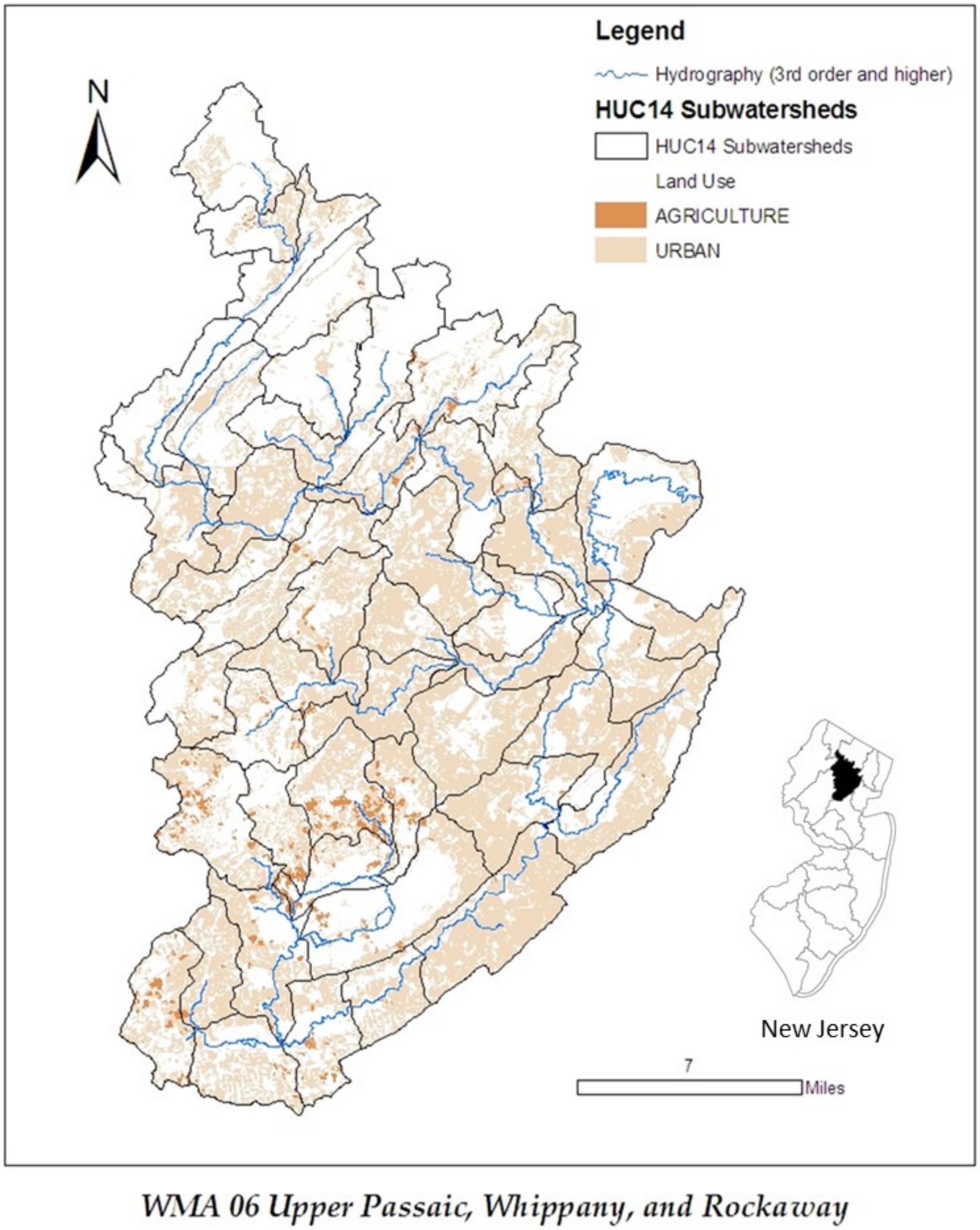


Figure 2-4. Generalized ternary diagram for landscape dominance (L_D).

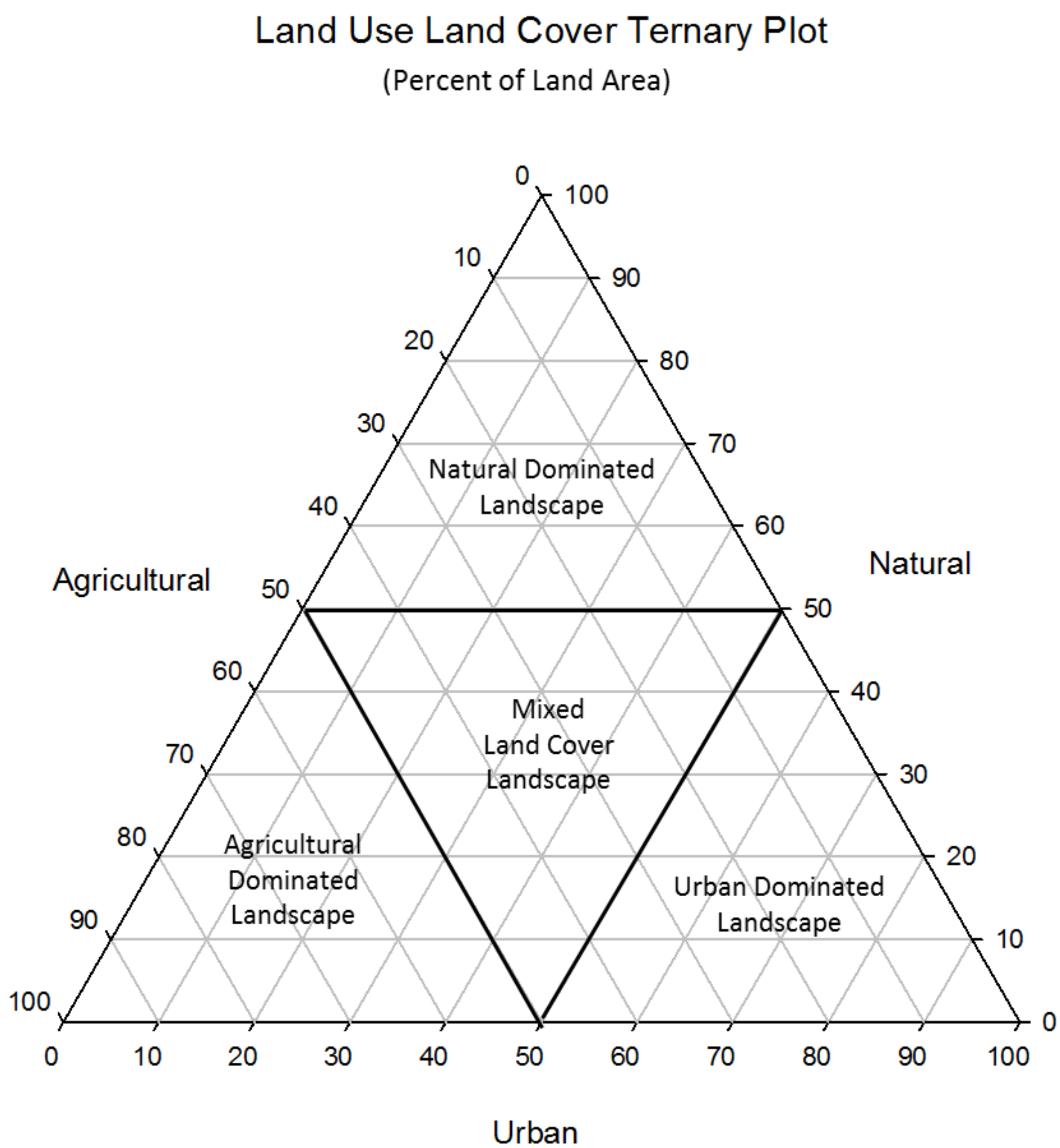


Figure 2-5a. L_D diagram for WMA 1.

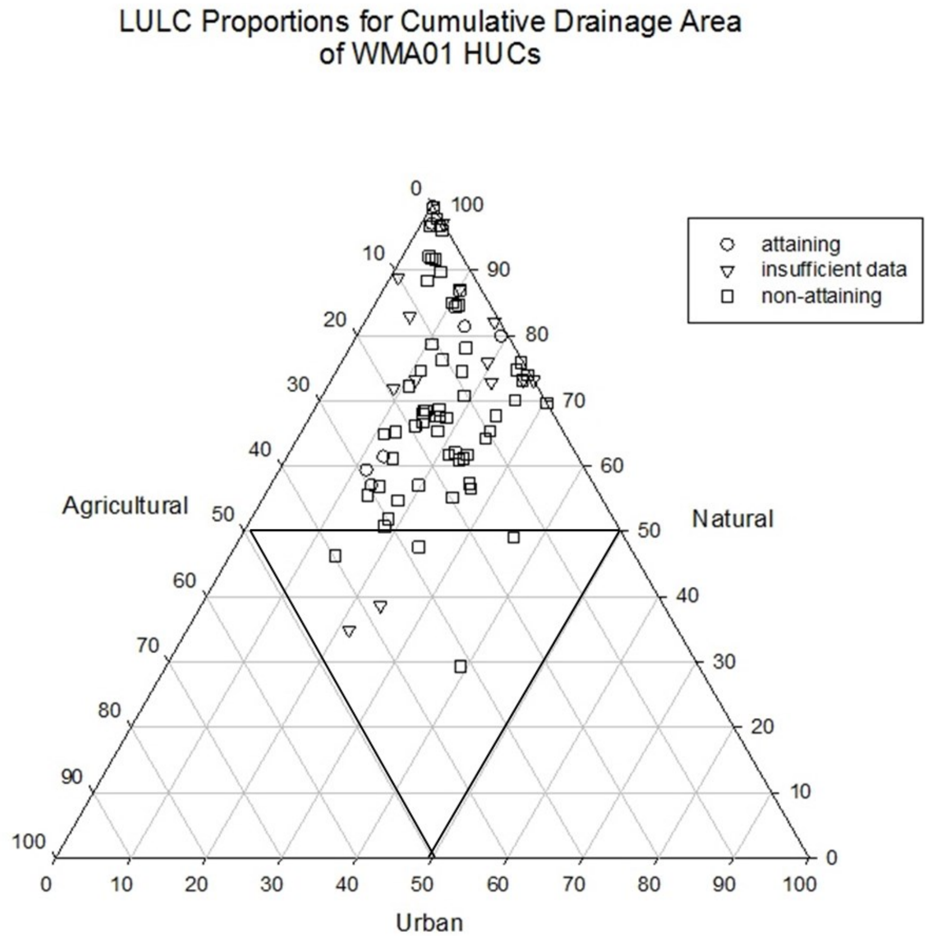


Figure 2-5b. L_D diagram for WMA 6.

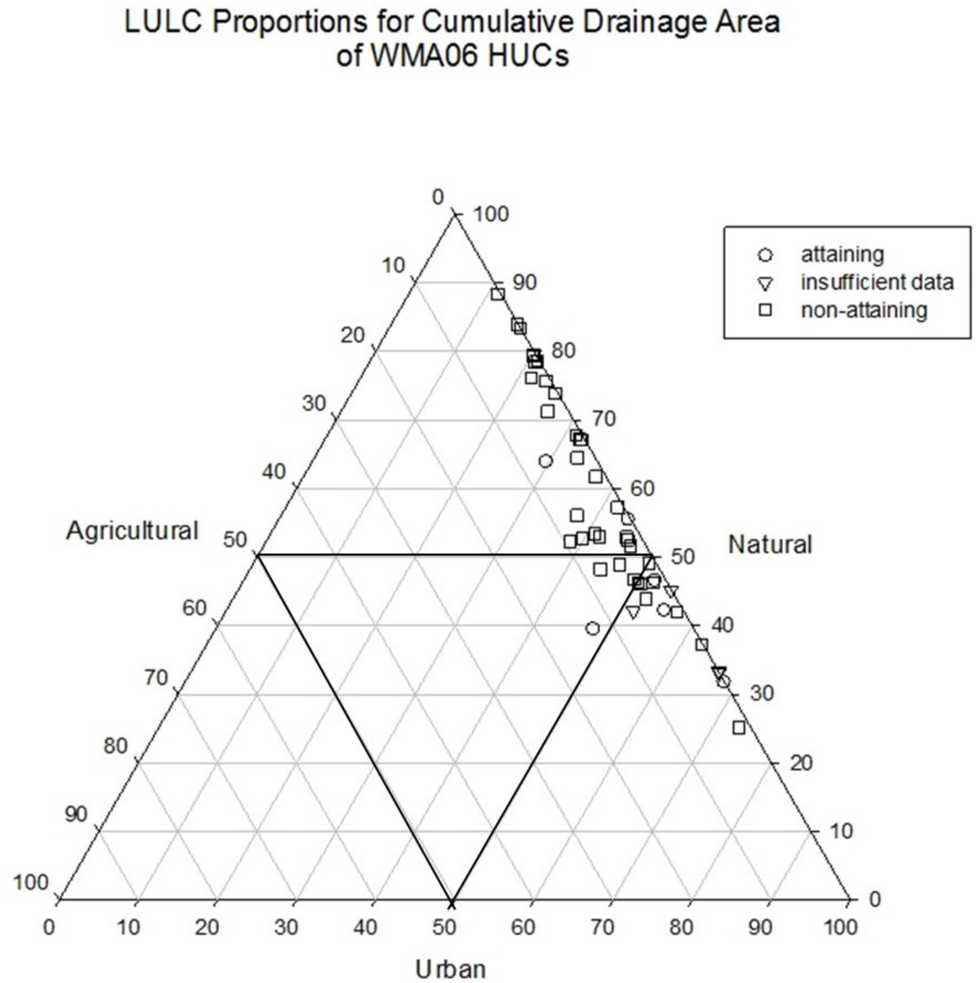


Figure 2-5c. L_D diagram for WMA 17.

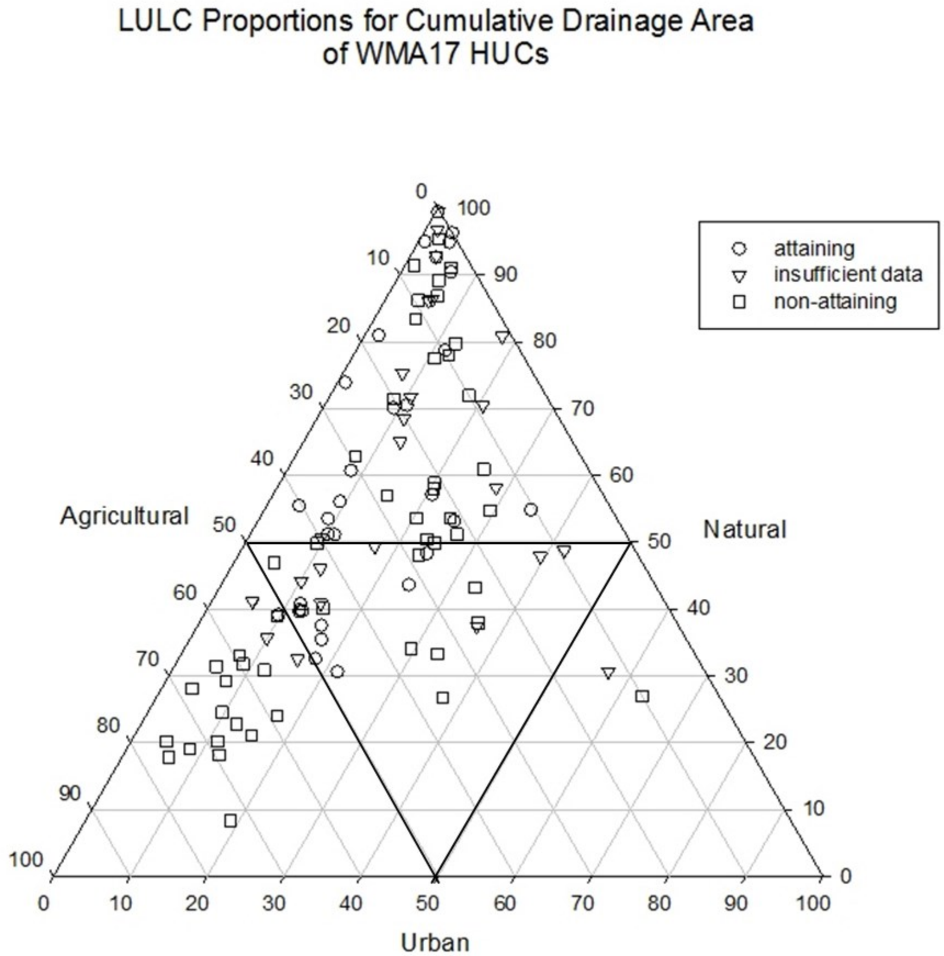


Figure 2-6. Subwatersheds and watershed management areas of New Jersey.

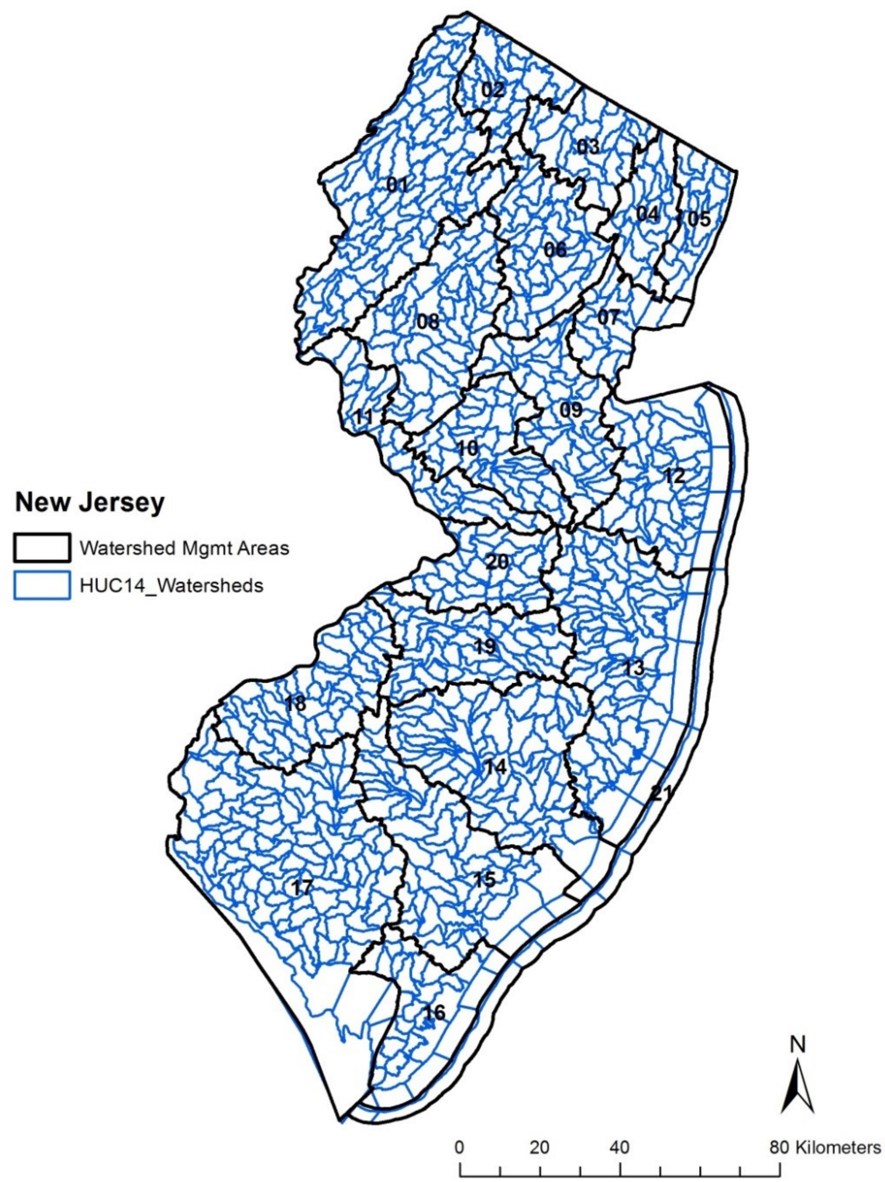


Figure 2-7. Ambient stream water chemistry sampling locations in New Jersey.

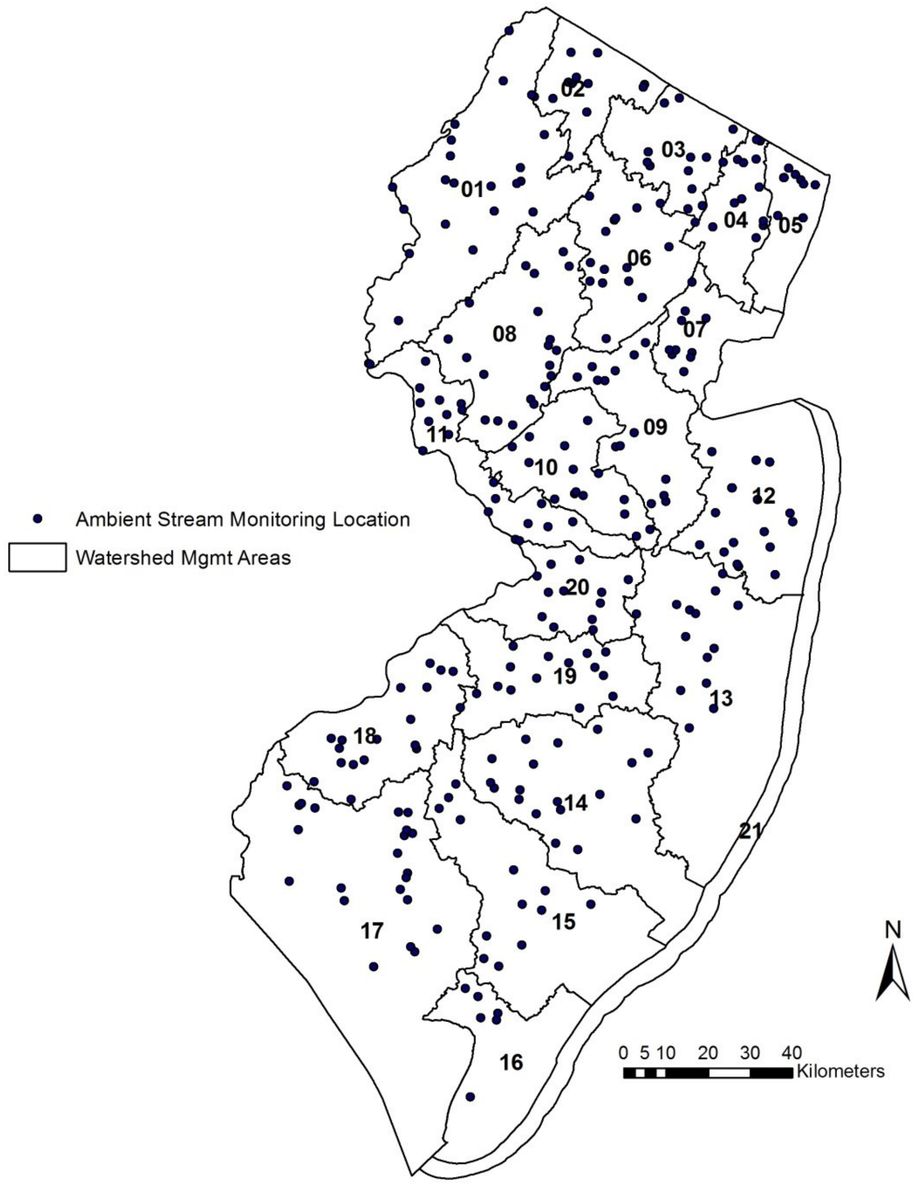


Figure 2-8. Ambient stream biomonitoring sampling locations in New Jersey.

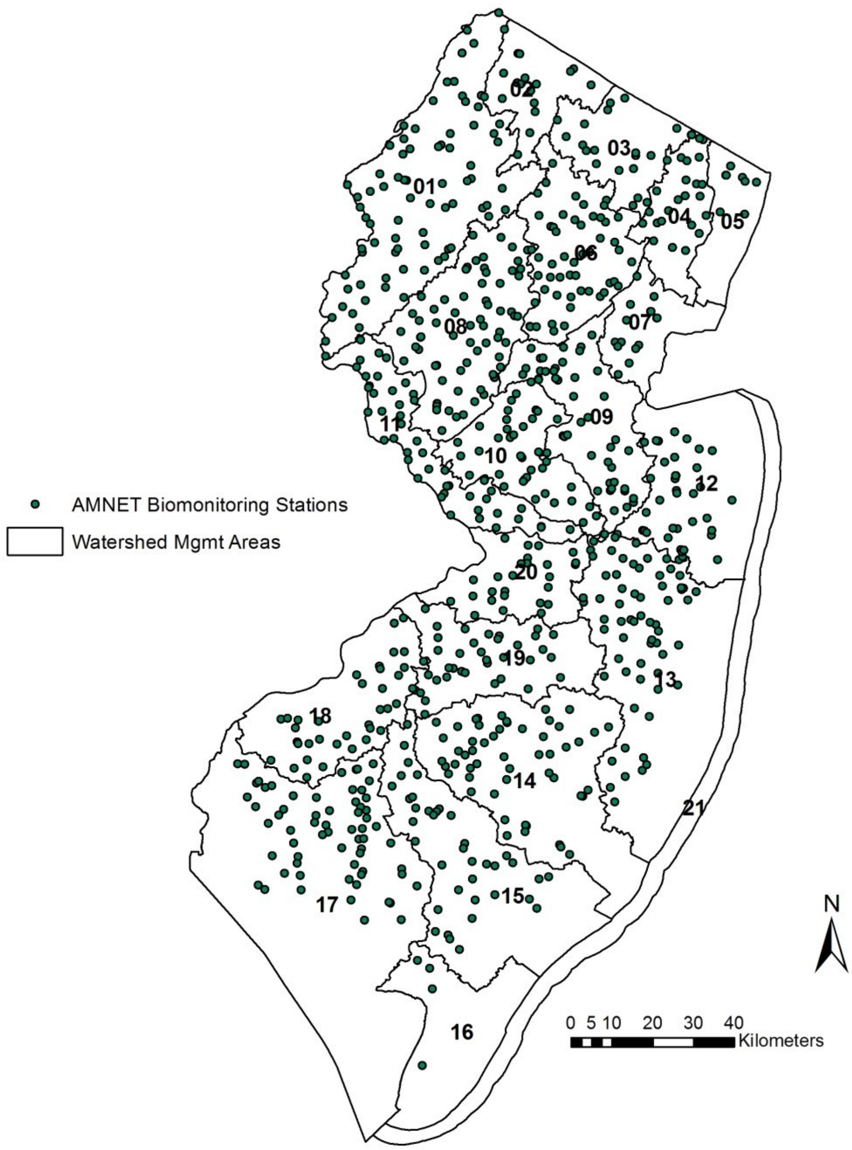
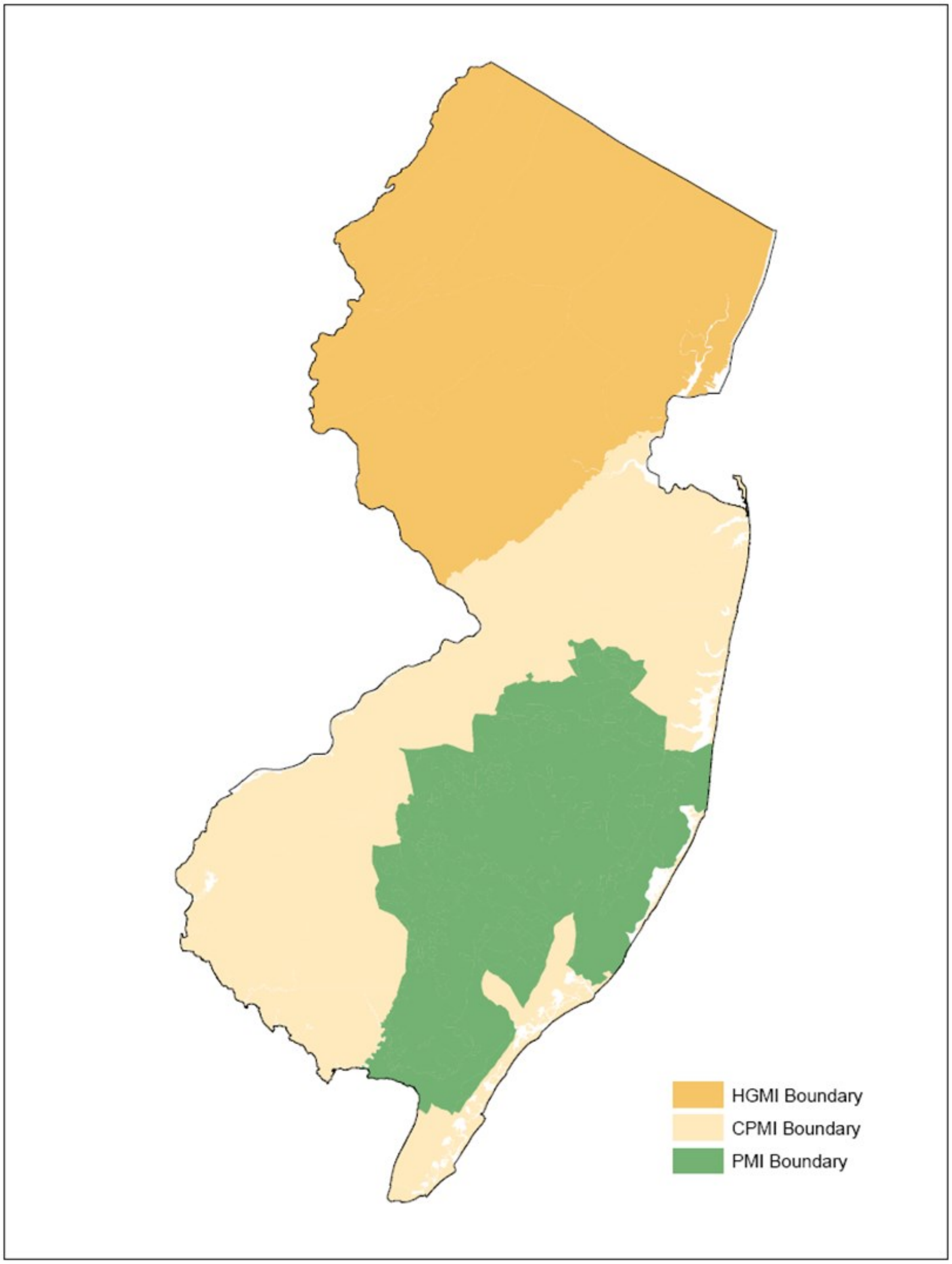


Figure 2-9. Macroinvertebrate Index zones of New Jersey.



(from NJDEP 2012a)

Figure 2-10. WMA 6 stream quality monitoring locations.

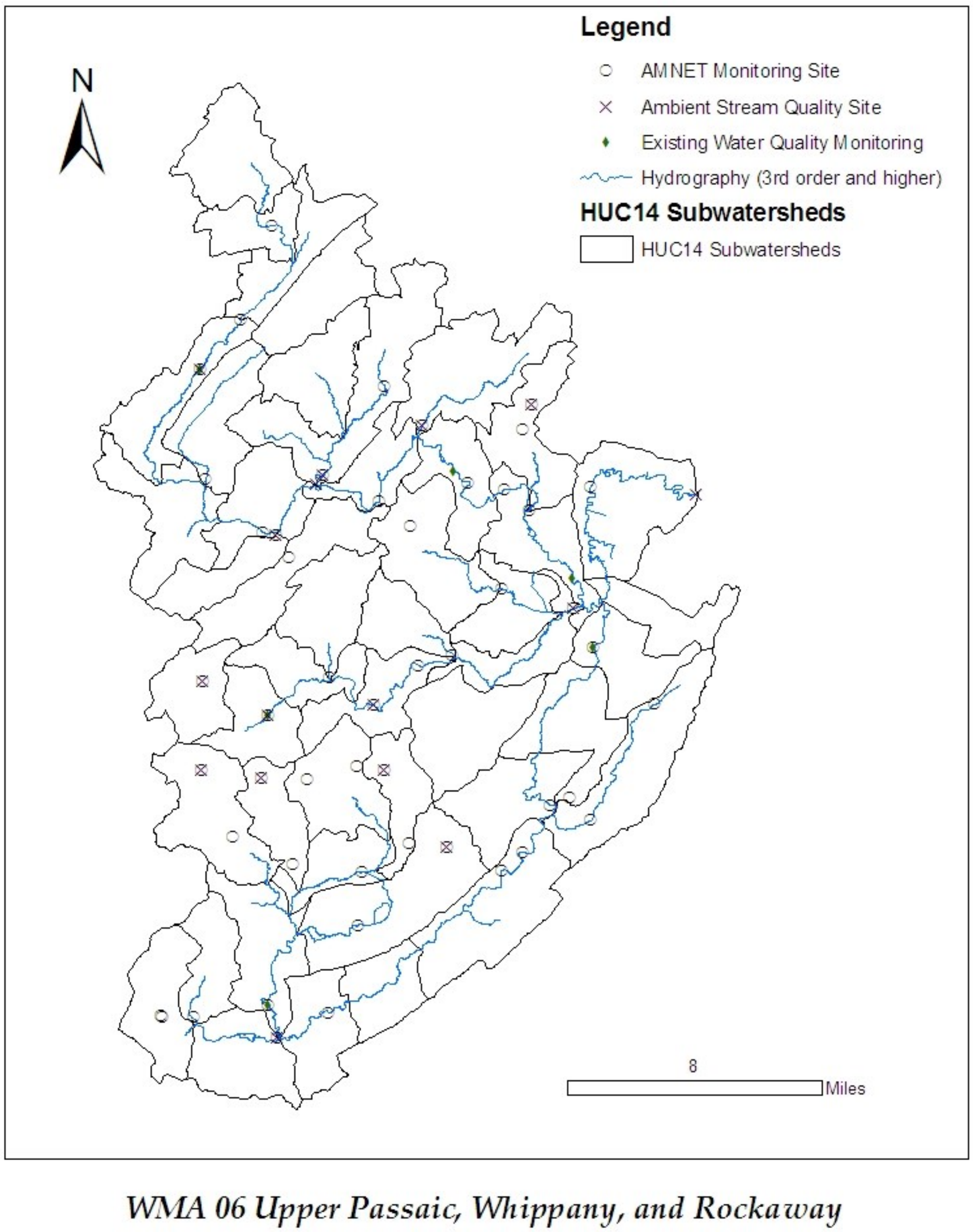
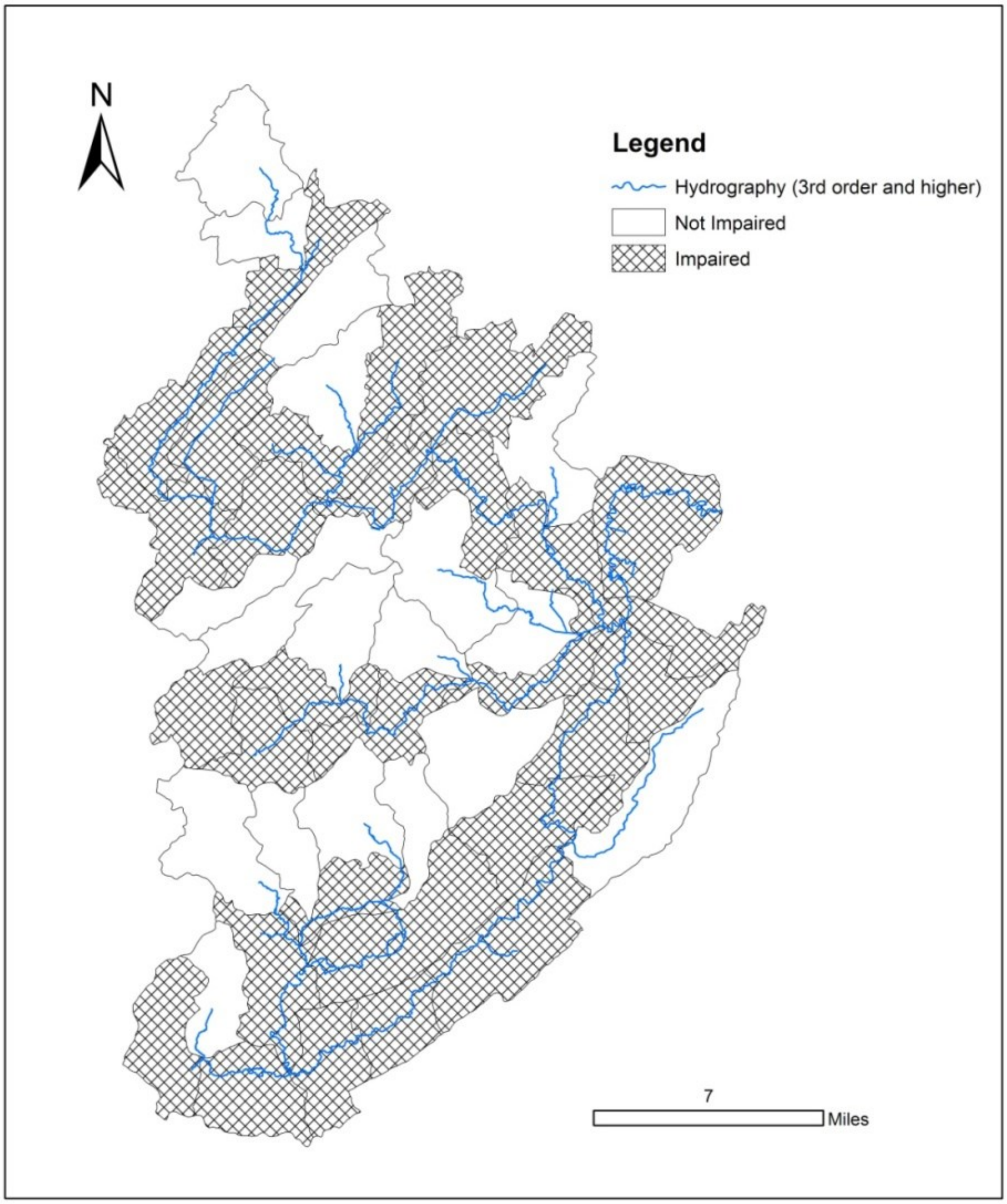


Figure 2-11. WMA 6 impaired subwatersheds.



WMA 06 Impaired Subwatersheds

Table 2-1. Summary data for watershed management areas 1, 6, and 17.

Watershed Management Area		Area (sq km)	Area (sq mi)	No. of HUC14 subwatersheds	Water Quality Management Planning Area
01	Upper Delaware	1,932	746	82	Sussex and Upper Delaware
06	Upper Passaic, Whippany, and Rockaway	936	362	46	Northeast
17	Maurice, Salem, and Cohansey	3,195	1,233	105	Lower Delaware and Tri-County

Table 2-2. Percent change in land use/land cover types 2002 to 2007.

Level I Anderson LULC (NJDEP-modified)	Change in HUC14 proportion 2002-2007	
	mean	median
Agricultural	-0.61%	-0.21%
Barren	-0.12%	-0.07%
Forest	-0.95%	-0.71%
Urban	1.75%	1.39%
Water	0.08%	0.05%
Wetlands	-0.16%	-0.11%

Table 2-3. Designated uses and data requirements for water quality assessment.

Designated Use	**Data Requirements**
Aquatic Life	If available, benthic macroinvertebrate and fin fish data, pH, DO, temperature, total phosphorus, TDS and TSS. DO is the minimum data requirement. (Temp & DO trout)
Recreation • **Primary and Secondary Contact** • **Aesthetics (Lakes only)**	Enterococcus, fecal coliform or E. coli Aesthetic listings are “carry-overs” and were assumed to be phosphorus related. The Department is developing a methodology to better assess lakes which should be available for the next assessment cycle.
Fish Consumption	Fish Consumption Advisories for one or more parameters
Shellfish Harvesting	Fecal coliform or total coliform
Drinking Water Supply	Metals, toxics, nitrate, TDS, chloride, and source water use restrictions. The minimum data requirement is nitrate.
Industrial Water Supply	TSS and pH
Agricultural Water Supply	TDS and salinity

Table 2-4. Watershed Management Area 06, subwatersheds, land use/land cover, and attainment status.

Water Quality Assessment Unit (HUC14 subwatershed)	Assessment Unit Name	Impaired (1=yes, 0=no)	Cumulative Drainage Area (hectares)	Agriculture (% drainage area)	Urban (% drainage area)	Natural (% drainage area)	Landscape L_D	Urban Number U_N	Impervious Cover (% drainage area)
02030103010010	Passaic R Upr (above Osborn Mills)	0	2,627	7.5%	39.8%	51.8%	Natural	0.151	9.4%
02030103010020	Primrose Brook	0	1,358	6.5%	29.5%	63.3%	Natural	0.128	7.7%
02030103010030	Great Brook (above Green Village Rd)	0	2,054	12.8%	47.7%	38.5%	Mixed	0.194	20.7%
02030103010040	Loantaka Brook	NA	1,311	6.4%	51.5%	41.3%	Urban	0.134	19.0%
02030103010050	Great Brook (below Green Village Rd)	1	6,059	9.3%	38.5%	51.2%	Natural	0.07	12.9%
02030103010060	Black Brook (Great Swamp NWR)	1	3,681	2.6%	26.2%	70.1%	Natural	0.053	11.0%
02030103010070	Passaic R Upr (Dead R to Osborn Mills)	1	14,673	6.5%	37.4%	55.0%	Natural	0.145	10.3%
02030103010080	Dead River (above Harrisons Brook)	1	1,970	7.5%	44.3%	47.7%	Mixed	0.168	13.7%
02030103010090	Harrisons Brook	0	1,412	1.5%	73.3%	24.8%	Urban	0.209	23.3%
02030103010100	Dead River (below Harrisons Brook)	1	5,386	3.9%	52.2%	43.4%	Urban	0.146	11.1%
02030103010110	Passaic R Upr (Plainfield Rd to Dead R)	1	21,792	5.6%	41.0%	52.4%	Natural	0.15	14.1%
02030103010120	Passaic R Upr (Snyder to Plainfield Rd)	1	23,198	5.3%	41.8%	52.0%	Natural	0.146	14.6%
02030103010130	Passaic R Upr (40d 45m to Snyder Ave)	1	26,422	4.7%	46.4%	48.0%	Mixed	0.163	17.4%
02030103010140	Canoe Brook	0	3,115	0.1%	62.6%	32.8%	Urban	0.118	26.6%
02030103010150	Passaic R Upr (Columbia Rd to 40d 45m)	1	31,717	3.9%	49.3%	45.4%	Mixed	0.141	19.8%
02030103010160	Passaic R Upr (HanoverRR to ColumbiaRd)	1	33,936	3.7%	50.0%	44.8%	Urban	0.147	20.8%
02030103010170	Passaic R Upr (Rockaway to Hanover RR)	1	35,723	3.5%	50.4%	44.6%	Urban	0.145	22.1%
02030103010180	Passaic R Upr (Pine Bk br to Rockaway)	1	90,619	1.9%	45.6%	49.5%	Mixed	0.179	21.8%
02030103040010	Passaic R Upr (Pompton R to Pine Bk)	1	93,697	1.8%	45.3%	49.9%	Mixed	0.117	15.3%
02030103020010	Whippany R (above road at 74d 33m)	1	1,570	1.4%	36.9%	60.1%	Natural	0.121	14.2%
02030103020020	Whippany R (Wash. Valley Rd to 74d 33m)	1	3,196	2.3%	33.2%	63.4%	Natural	0.17	31.6%
02030103020030	Greystone / Watnong Mtn tribs	0	2,014	2.4%	55.3%	41.6%	Urban	0.165	25.7%
02030103020040	Whippany R(Lk Pocahontas to Wash Val Rd)	1	6,665	2.0%	46.4%	50.5%	Natural	0.285	30.8%
02030103020050	Whippany R (Malapardis to Lk Pocahontas)	1	8,409	1.8%	51.8%	45.2%	Urban	0.187	47.5%
02030103020060	Malapardis Brook	0	1,319	0.1%	68.1%	30.2%	Urban	0.173	34.6%
02030103020070	Black Brook (Hanover)	NA	2,691	0.0%	66.7%	32.6%	Urban	0.215	38.4%
02030103020080	Troy Brook (above Reynolds Ave)	NA	2,608	0.1%	66.8%	27.0%	Urban	0.136	32.8%
02030103020090	Troy Brook (below Reynolds Ave)	NA	4,175	0.1%	54.8%	40.8%	Urban	0.218	34.1%
02030103020100	Whippany R (Rockaway R to Malapardis Bk)	1	18,050	0.9%	57.1%	40.2%	Urban	0.123	3.6%
02030103030010	Russia Brook (above Milton)	0	2,219	0.0%	16.6%	81.1%	Natural	0.115	5.7%
02030103030020	Russia Brook (below Milton)	0	3,474	0.7%	20.9%	76.0%	Natural	0.099	6.6%
02030103030030	Rockaway R (above Longwood Lake outlet)	1	5,211	0.6%	23.7%	72.6%	Natural	0.057	5.9%
02030103030040	Rockaway R (Stephens Bk to Longwood Lk)	1	7,277	0.5%	20.3%	76.7%	Natural	0.05	2.9%
02030103030050	Green Pond Brook (above Burnt Meadow Bk)	0	1,912	0.4%	11.3%	71.7%	Natural	0.128	9.7%
02030103030060	Green Pond Brook (below Burnt Meadow Bk)	1	3,960	0.2%	21.2%	68.8%	Natural	0.173	9.8%
02030103030070	Rockaway R (74d 33m 30s to Stephens Bk)	1	13,596	0.4%	25.8%	69.5%	Natural	0.196	25.4%
02030103030080	Mill Brook (Morris Co)	0	1,268	0.9%	50.0%	48.9%	Urban	0.238	14.5%
02030103030090	Rockaway R (BM 534 brdg to 74d 33m 30s)	1	16,764	0.4%	32.5%	63.4%	Natural	0.061	8.8%
02030103030100	Hibernia Brook	0	2,055	0.1%	15.9%	82.6%	Natural	0.065	8.8%
02030103030110	Beaver Brook (Morris County)	1	5,884	0.2%	20.3%	72.1%	Natural	0.139	25.7%
02030103030120	Den Brook	0	2,337	1.4%	52.0%	41.4%	Urban	0.111	5.2%
02030103030130	Stony Brook (Boonton)	1	3,185	2.2%	21.6%	71.6%	Natural	0.156	14.5%
02030103030140	Rockaway R (Stony Brook to BM 534 brdg)	1	26,354	0.6%	32.2%	62.4%	Natural	0.169	14.1%
02030103030150	Rockaway R (Boonton dam to Stony Brook)	1	31,328	0.7%	31.5%	62.1%	Natural	0.19	14.3%
02030103030160	Montville tribs.	0	2,052	0.4%	44.1%	53.0%	Natural	0.133	10.0%
02030103030170	Rockaway R (Passaic R to Boonton dam)	1	53,511	0.8%	42.0%	53.1%	Natural	0.11	21.7%

indicates subwatersheds with insufficient data to determine impairment status

Table 2-5. Chi-Square test of contingency table for Coastal Plain Macroinvertebrate Index and L_D

Chi-Square Contingency Table
Benthic - IBI, Coastal Plain Macroinvertebrate Index
n=198

	Attaining		Not Attaining		
Subjects	**Excellent**	**Good**	**Fair**	**Poor**	
Agriculture Dom	1	3	22	9	Counts
	2.652	6.54	18.561	7.247	Expected Counts
	2.857	8.571	62.857	25.714	Row %
	6.667	8.108	20.952	21.951	Column %
	0.505	1.515	11.111	4.545	Total %
Mixed	5	11	30	9	Counts
	4.167	10.278	29.167	11.389	Expected Counts
	9.091	20	54.545	16.364	Row %
	33.333	29.73	28.571	21.951	Column %
	2.525	5.556	15.152	4.545	Total %
Natural Dom	9	18	15	11	Counts
	4.015	9.904	28.106	10.975	Expected Counts
	16.981	33.962	28.302	20.755	Row %
	60	48.649	14.286	26.829	Column %
	4.545	9.091	7.576	5.556	Total %
Urban Dom	0	5	38	12	Counts
	4.167	10.278	29.167	11.389	Expected Counts
	0	9.091	69.091	21.818	Row %
	0	13.514	36.19	29.268	Column %
	0	2.525	19.192	6.061	Total %

Chi-square= 33.252 with 9 degrees of freedom. (P = <0.001)

The proportions of observations in different columns of the contingency table vary from row to row.
The two characteristics that define the contingency table are significantly related. (P = <0.001)
Power of performed test with alpha = 0.050: 0.995

Table 2-6. Chi-Square test of contingency table for High Gradient Macroinvertebrate Index and L_D

Chi-Square Contingency Table
Benthic - IBI, High Gradient Macroinvertebrate Index
n=367

	Attaining		*Not Attaining*		
Subjects	**Excellent**	**Good**	**Fair**	**Poor**	
Mixed	11	26	35	6	Counts
	13.929	20.143	30.429	13.5	Expected Counts
	14.103	33.333	44.872	7.692	Row %
	16.923	27.66	24.648	9.524	Column %
	3.022	7.143	9.615	1.648	Total %
Natural Dom	53	61	59	24	Counts
	35.179	50.874	76.852	34.096	Expected Counts
	26.904	30.964	29.949	12.183	Row %
	81.538	64.894	41.549	38.095	Column %
	14.56	16.758	16.209	6.593	Total %
Urban Dom	1	7	48	33	Counts
	15.893	22.984	34.72	15.404	Expected Counts
	1.124	7.865	53.933	37.079	Row %
	1.538	7.447	33.803	52.381	Column %
	0.275	1.923	13.187	9.066	Total %

Chi-square= 75.604 with 6 degrees of freedom. (P = <0.001)

The proportions of observations in different columns of the contingency table vary from row to row.
The two characteristics that define the contingency table are significantly related. (P = <0.001)
Power of performed test with alpha = 0.050: 1.000

Table 2-7. Odds Ratio tests for impact of L_D on water quality (as B-IBI).

L_D	tested outcome	Odds Ratio	95% CI Odds Ratio Lower	Upper	n	alpha (α)	P-value
Urban	Not Attaining	11.0	6.1	19.9	724	0.05	<0.001
Agriculture	Not Attaining	5.0	2.1	12.3	609	0.05	<0.001
Natural	Attaining	3.9	2.9	5.4	759	0.05	<0.001

Table 2-8. Results of logistic regression model for probability that subwatershed is impaired given the percentage of urban LULC.

Logistic regression model for New Jersey HUC14 subwatersheds and impairment status based on B-IBI scores

n=759

Regression equation: $\ln(Y/1-Y) = -0.896+(0.0432*\text{urban LULC percent})$

Goodness of fit measures for the overall model:

		P-value
Likelihood Ratio Test Statistic:	118.4	<0.001
Hosmer-Lemeshow Statistic:	8.143	0.42

Details of regression analysis:

Independent variable:	Coefficient	Std. Error	Wald Statistic	P value
Intercept	-0.896	0.145	38.36	<0.001
Urban, percent of watershed	0.0432	0.00457	89.17	<0.001

Table 2-9. Results of multiple logistic regression model for probability that subwatershed is impaired given the percentages of urban and agricultural LULC.

Logistic regression model for New Jersey HUC14 subwatersheds and impairment status based on B-IBI scores

n=759

Regression equation: ln(Y/1-Y) = -1.337+(0.0485*urban LULC percent)+(0.0179*Ag LULC percent)

Goodness of fit measures for the overall model:

		P-value
Likelihood Ratio Test Statistic:	131.3	<0.001
Hosmer-Lemeshow Statistic:	8.99	0.34

Details of regression analysis:

Independent variable:	Coefficient	Std. Error	Wald Statistic	P value	VIF
Intercept	-1.337	0.195	46.94	<0.001	
Urban, percent of watershed	0.0485	0.00489	98.36	<0.001	1.16
Agriculture, percent of watershed	0.0179	0.00502	12.64	<0.001	1.16

Chapter 3 Spatial analysis for watershed-based water quality management

Abstract

This research focused on spatial factors that may influence implementation of a watershed (i.e., regional) approach for surface water quality assessments and management. Specifically, this study examined 1) the collinearity of land cover and land use across subwatersheds (HUC14) nested in larger mesoscale watersheds (HUC11), in New Jersey, 2) spatial patterns of urban land use among the 46 subwatersheds of Watershed Management Area 6 in northern New Jersey, and 3) spatial dependency or spatial autocorrelation between several landscape attributes commonly reported to predict water quality and aquatic ecosystem health in urbanizing watersheds. The landscape attributes considered by subwatershed were proportion of urban land cover, proportion of agricultural land use, number of permitted wastewater dischargers, proportion of impervious surface, total cumulative drainage area for each subwatershed, and urban number, a metric encompassing both density and degree of fragmentation of urban land use patterns. Statistical analytic methods and GIS-based spatial analysis tools were used to analyze the relationship between the attribute variables described above, assess the degree of spatial autocorrelation among subwatersheds, and perform spatial regression on possible explanatory variables (e.g., land use, surface water discharges and impervious surface). This research shows that agricultural land, natural land cover and urban LULC are all negatively correlated across the study area, with a strong negative correlation between natural and urban lands. The response variable for this study was watershed impairment status: impaired or not impaired. The logit function was used to transform

the binary response variable to a continuous variable for regression analysis. Regression analysis of watershed characteristics with the probability that a subwatershed is impaired indicated a significant relationship for only cumulative drainage area and impervious surface cover. The investigation of spatial dependence between subwatersheds for the parameters tested did not indicate conclusive results, highlighting the complexity of water quality-land use-regulatory linkages.

3.1 Introduction

Based upon 1:24,000-scale mapping of rivers and streams conducted by NJDEP, there are 11,702 miles of non-tidal rivers and streams and 6,424 miles of tidal rivers and streams (NJDEP 2006). In addition, the 20 WMAs comprise 970 subwatersheds at the HUC14 level.

Effective management of water resources must include regular monitoring and assessment of watershed conditions (NRC 1999, p.112). In the 1990s, the USEPA began delegating authority for monitoring and assessment of intrastate waterbodies to the respective individual states. This included information regarding whether waterbodies were meeting their designated uses, as defined by water quality standards. The primary mechanisms from the CWA to accomplish monitoring and assessment of US waters are the Water Quality Inventory (WQI) Report (Section 305(b)) and the Impaired Waterbodies List (Section 303(d)). These had been considered separate tasks and deliverables for many years, but beginning in 2002, the USEPA required states to submit an Integrated Water Quality and Monitoring Report which would include both the WQI report and the Section 303(d) list of impaired waters, along with other relevant information including plans to improve the monitoring and assessment capability and data quality.

As discussed in the previous chapter, land cover and land use has been widely used to explain some of the variation in water quality and aquatic biological integrity both across regions and within watersheds. Hunsaker and Levine (1995) point out that rivers and streams are useful indicators of cumulative effects because they aggregate the effects of pollution from runoff and aerial deposition and also the effects of hydrological impacts. Scale, both across basins (Utz et al. 2009 and Tate et al. 2005) and within watershed drainages (Alberti et al. 2007, Fohrer et al. 2002, and Bolstad and Swank 1997) has been shown to be a factor in the impact of land use and land cover (LULC) on the quality of surface water and the health and integrity of aquatic ecosystems. These studies used water chemistry or benthic macroinvertebrate sampling to test relationships between LULC and freshwater aquatic environments and are generally in agreement that an effect exists. However, the magnitude of the impact and questions of threshold effects remain. Utz et al. (2009) reported thresholds for macroinvertebrate population integrity between 50%-60% of a watershed in urban LULC, with some of the variability attributed to watersheds in different physiographic regions.

Both King et al. (2005) and Strayer et al. (2003) used empirical models and data for the Chesapeake Bay watershed to assess changes in water quality with LULC at the watershed-wide scale and using a distance-weighted buffer approach. These investigations indicated that the impact of scale and proximity were different depending on the response variable, but did not report any threshold effects. Tong and Chen (2002) used a distributed hydrologic model to predict water quality impacts from various land uses in the Little Miami River watershed in Ohio, USA, but also did not report any threshold effect, such as indicated by Utz (2009).

One common thread between the earlier investigations is that scale and space seem to matter when assessing the relationship between LULC and water quality in streams and rivers. Regression and correlation techniques, especially ordinary least squares (OLS) are common empirical approaches to develop and investigate relationships between a response variable and variables that may provide some explanation of that response. However, these methods assume stationarity in space, which is often not a valid assumption for environmental data or other information with a significant geographic (i.e., spatial) variability. In addition to studies of watersheds, examples include regional development (Yu and Wei 2007), distribution of crime (Fotheringham 2000), vegetation patterns and precipitation (Propastin et al.), and occurrences of health effects (Anselin 2005). Bockstael (1996) points out that both hedonic price models and models of land use conversion, useful for predicting water quality impacts, contain spatially correlated variables.

Due to the natural spatial relationship of geographic-dependent data, traditional methods for modeling the relationship, such as OLS, can be improved by understanding and explicitly including information on spatial dependence among and between variables.

The broad goal of this study is to highlight important spatial issues in the analysis of the impact of land use and land cover on water quality in the context of watershed management. Specific objectives of this research aimed to explore three key factors underlying studies of watersheds and LULC change: 1) collinearity of LULC proportions in both subwatersheds (HUC14) and mesoscale watersheds (HUC11), 2) spatial distribution and pattern of urban landscapes in watersheds, and 3) spatial autocorrelation of impaired watersheds and LULC within those watersheds. These three factors have significant implications for management of water quality through regulations and policy.

3.2 Methods

Because watersheds are spatially connected and land use and land cover patterns are by their nature geographic and therefore spatially interesting, the first effort to understand the possible significance of the spatial relationship was through exploratory spatial data analysis (ESDA). This study includes an analysis of both global and local spatial autocorrelation among land use characteristics of subwatersheds and an analysis of spatial dependence of those characteristics with the probability that a subwatershed listed as impaired on the Clean Water Act (CWA) 303(d) list of waterbodies not attaining one or more designated uses. Additionally, this study investigated the degree of global spatial autocorrelation in the land cover data for HUC14s in WMA 6 using the global Moran's I (Yu and Wei 2007). The Moran's I statistic provides an estimate of the degree of spatial clustering (positive spatial autocorrelation, larger I) and spatially dissimilar areas (negative spatial autocorrelation, smaller I). The spatial weights matrix describes the linkage by which values are weighted for further analysis. In this research, spatial units are subwatersheds, the units used for water quality assessment in New Jersey. The spatial weights matrix is a critical component in tests of global and local spatial autocorrelation. Following Anselin (2005), this study examined contiguity, spatial units that share a border, and distance-based spatial weights.

3.2.1 Study area

This study focused on Watershed Management Area (WMA) 6, which includes the upper Passaic watershed in northern New Jersey, USA. WMA 6 covers 361 square miles of northern New Jersey and includes portions of Essex, Union, Sussex, Somerset and Morris counties and 52 municipalities. WMA 6 is made up of the 46 subwatersheds listed in Table 3-1. Based on digital maps and 2002 land cover/land use data downloaded from the NJDEP Geographic Information Systems (GIS) website (NJDEP 2014, last accessed March 2014), WMA 6 has 5,642 acres (2.4%) in agricultural use, 150,328 acres (65%) urban lands, and an estimated 50,159 acres (22%) of impervious surface. Other land uses are present in WMA 6 including wetlands and forests, and are mapped as all the areas not shown as urban or agricultural. WMA 6 was chosen for its mix of LULC and because it has one of the most complete data sets available of the WMAs in New Jersey. Figure 3-1 shows the spatial extent of agricultural and urban land use in WMA 6.

3.2.2 Collinearity of land use and land cover

A Pearson product moment correlation technique was used to test the relationship between the three LULC categories used previously in this dissertation: natural, urban and agricultural land covers. These have been shown previously to be predictors of water quality and aquatic ecological outcomes (Alberti 2007 and Kennen 1998). The choropleth maps in Figures 3-2, 3-3, and 3-4 show the percent of urban, natural and agricultural LULC, respectively. The map unit boundaries in the choropleth maps represent the HUC14 subwatersheds of New Jersey.

This study also examined the relationship between impervious surface cover and areas mapped as urban landscape. Due to concerns of normality in the smaller sample size for the impervious surface data, Spearman Rank Correlation technique was used to test relationship between urban land cover and impervious surface coverage. This relationship was tested across mesoscale watersheds and subwatersheds. Correlations were calculated using aggregate data from New Jersey's 20 Watershed Management Areas, and by Spearman Rank Correlation of impervious surface as a percent of subwatershed area and urban land cover as a percent of subwatershed area for 233 HUC14s in WMAs 1, 6, and 17. Figure 3-5 shows the locations of WMAs 1, 6, and 17. As noted previously in this dissertation, these three WMAs were chosen for the differences in LULC and their location in three distinct physiographic regions of New Jersey. The HUC14 subwatersheds are the smallest watershed unit mapped by the NJDEP and it is the assessment unit for water quality. The average size of a HUC14 in New Jersey is 8.5 square miles.

3.2.3 Spatial extent of water quality assessment units

The CWA requires states to report the results of monitoring and assessment conducted at point locations as extrapolated results. The reporting units are typically linear miles for streams in the inventory section of the Integrated Report and discrete waterbodies for the 303(d) section of the Integrated Report. In 2006, the NJDEP changed its definition of assessment unit to maintain a somewhat artificial assessment rate. Prior to 2006, the NJDEP used stream order to extrapolate results from a monitoring station to a spatial extent measured as stream miles. This served as the definition of spatial extent for assessment units until 2006. Around 2004, the NJDEP changed the scale of the base resolution of stream coverages from 1:100,000 to 1:24,000.

As a result of this change, smaller streams were mapped and the ratio of unassessed/assessed stream miles increased. Anticipating a future increase in base resolution for the stream and river coverage to 1:2,400, and to avoid a large increase in number of unassessed stream miles the NJDEP (2006a, Appendix G) developed a new definition of spatial extent for assessment units. The new spatial extent for stream assessment units was watershed-based. Results indicating whether or not designated uses are attained at a point monitoring station are extrapolated to the entirety of whatever HUC14 watershed within which that station falls. In this way, the attainment or non-attainment of designated uses is extrapolated to all waters within the respective HUC14.

The NJDEP considers this new approach to be "more conservative" (i.e., protective) because any impairment as measured by point location analyses will result in a listed impairment for the entire subwatershed. Additionally, for each HUC14 with multiple designated use classifications, the most stringent classification will be used for the determination of impairment for the entire HUC14. It is worth noting that a negative sample result (i.e., non-detect or very low levels of pollution) will result in the entire watershed being declared to attain the designated uses for all waters within the watershed, because the subwatershed is the assessment unit. Even with the new watershed-based spatial extent methodology, the NJDEP has assessed all designated uses in only88 (~10%) of the 970 HUC14 subwatersheds. Full assessment of all designated uses except fish consumption has been achieved in only 241 (~25%) of the assessment. This shows the clear need for a statistically-based approach using readily available information, which has similar spatial extent to the spatial extent used for assessment, to assess the likelihood of meeting or not meeting designated uses in New Jersey's subwatersheds.

3.2.3 Watershed impairment

One way to check the success of using subwatersheds as the spatial extent for quantifying and listing impaired waterbodies in the Integrated Report based on relatively sparse point location monitoring sites is to incorporate or create a metric that can be used as a proxy for cumulative effects as measured by biological, physical and chemical changes in the aquatic environments being assessed. As discussed previously, many researchers have modeled various watershed characteristics in an effort to relate them to degradation in aquatic ecosystems. In New Jersey, degradation of aquatic ecosystems is the primary cause of waterbodies not being able to meet their designated use goals and thereby being listed on the 303(d) list (sublists 4 and 5 of the Integrated Report).

Schueler (1994) indicated positive correlations between the percent of impervious cover in a watershed or on a site and the amount of runoff, phosphorus loading and stream channel instability, and a negative correlation between percent impervious surface and macroinvertebrate populations. Bolstad and Swank (1997) showed that the cumulative impact of increasing urban and agricultural land use along a downstream gradient resulted in measurable and significant impacts on stream water quality, especially during peak discharge events. Bockstael (1996) showed a strong relationship between nitrogen loading and land use, where residential and agricultural land uses were reported to account for more than 83% of the nitrogen loading to the Patuxent watershed in eastern Maryland. Lathrop et al. (2007) used an impervious cover threshold of 10% (using HUC11 watersheds) to indicate degradation in watersheds in the New Jersey and New York Highlands. The results of this study, discussed in subsequent sections, does not support a 10% threshold effect at the subwatershed (HUC14) scale.

The weight of evidence from these studies and many others points to a significant and measurable relationship between land use, particularly urban and agricultural, and stream health and aquatic ecosystem integrity. In this study we use these “surrogates” to test the NJDEP’s spatial extent extrapolation method for listing impaired subwatersheds.

The quality of water in streams and hence the ability to meet designated uses in a waterbody is directly related to the source and transport of the water prior to it entering the waterbody. In this sense, this investigation seeks to define relationships for each of the explanatory variables that represent those sources and transport phenomena. These can be summed up by three major categories: direct runoff from the land surface, return flows via wastewater discharge, and groundwater discharge to the waterbody. This study did not include groundwater discharge, because it is not considered a significant contribution of contaminants to streams in WMA 6 (NJDEP 2006a).

Additionally, this investigation tests the hypothesis that landscape metrics (including wastewater discharge) can be used to estimate the likelihood that a given assessment unit, a HUC14 subwatershed, is impaired. This has broad implications for water resource management. As waterbodies are listed on the 303(d) list of impaired waters, it triggers a more extensive targeted monitoring and possible development of a remedial action. The remedial action typically will take one of three forms: development of a total maximum daily load (TMDL), watershed restoration projects or water-quality based effluent limits (WQBEL). These are expensive projects to implement and have long-term planning horizons, thus making the determination of a waterbody meeting designated uses (impairment status) an important policy and management decision.

3.2.4 Metrics

This investigation of the potential influence of spatial autocorrelation in watershed-based assessment of water quality included several variables commonly considered independent factors that influence water quality and aquatic ecosystem health and integrity. The variables included in this study included: 1) percent of the watershed in agricultural LULC, 2) the percent of the watershed in urban LULC, 3) the percent of the watershed in impervious cover, 4) the number of wastewater dischargers in a subwatershed, 5) a subwatershed's urban number (defined later in this chapter), and 6) the size of the drainage area. The dependent variable was the logit transform of the probability that a given subwatershed was impaired.

Under the Clean Water Act (CWA) and the regulations that implement it, states are required to assess water quality in the waters of the state and report the findings to the USEPA and the public. Assessment units that do not meet one or more designated uses are "listed" as impaired on the 303(d) list in integrated reports once every two years.

Because the assessment unit is listed as impaired or not impaired, it is a binary variable. A binary response variable cannot be tested using ordinary least squares linear regression. This lack of fit for binary response variables also applies to tests of spatial autocorrelation.

In order to perform the spatial analysis in this study, the "impaired" variable was logit transformed. The logit transform transforms the non-linear relationship, between the explanatory variable and the probability that the response is one of two outcomes, to a linear one. This also keeps the predicted response bounded between 0 and 1. The logit transform is the natural log of the ratio of the probability of one outcome to the probability of the other outcome (e.g., probability of a subwatershed being impaired and the probability that it is not impaired).

Use of the maximum likelihood estimator with the logit transform allows for relaxation of the error structure assumptions that variance be constant and normally distributed. This is important to be able to assess the fit of the predicted response to observed responses (probabilities) and be able to assess the significance of the estimated parameters (regression coefficients). This technique has been used extensively for other applications including analysis of variables (ANOVA) with strong spatial dependence. Some examples include: prediction of landslide hazards (Ohlmacher and Davis 2003), ecological spatial prediction of wetland plant occurrence (van Horssen et al. 2002), and spatial pattern of farmland in the Maotiao River Basin, China (Huang et al. 2007).

3.2.4.1 Urban Number

The impact of urban landscape on water quality has been indicated to be related to both the overall amount of urban LULC and also the pattern or fragmentation of that landscape. Alberti et al. (2007) found a correlation between mean patch size of urban parcels and benthic macroinvertebrate integrity index in watersheds draining to Puget Sound, Washington. Similarly, Conway and Lathrop (2005) created a spatially-explicit urban build-out model that included a measure of fragmentation to predict potential future impacts on nonpoint source pollution in urbanizing watersheds in New Jersey.

The variable *urban number* is introduced in this study as a single variable that captures both the amount of watershed in urban landscape and the pattern of that urban land across the watershed. Urban number, U_N, is a dimensionless number equal to the urban patch density multiplied by the median patch size for a given watershed (see Equation 3-1).

$$U_N = \left(\frac{n}{A}\right) \times S \qquad \text{(Eq. 3-1)}$$

where, n = the number of urban patches in the subwatershed
A = total area of the subwatershed, and
S = median patch size

Unit area (A) and patch size (S) must be in the same units, for example acres, hectares, or km^2. The dimensionless characteristic of U_N may be beneficial in future investigations for ease of use in mathematical constructs or models of urban landscape.

3.3 Results and Discussion

It was a goal of this research to analyze differences in scale on the overall impact of LULC on water quality. Scale differences are important factors in the design of monitoring strategies for environmental systems, including watershed-based water quality monitoring (Strayer et al. 2003). Scale is also a determining variable for designing, organizing and ultimately funding watershed restoration and management programs (Wang 2001). A literature and database search of available data sets for all HUC14 subwatersheds indicated that complete data sets did not exist for most variables of interest in this study. As mentioned previously, one watershed management area, WMA 6, had the most complete and robust data sets, and so is used for the spatial analysis presented here.

3.3.1 Collinearity of land use and land cover

The research presented here confirmed that the amount LULC category in a given watershed in the study area is not independent of the other land covers in that watershed (Booth and Jackson 1997, and Alberti et al. 2007). A Pearson product moment correlation matrix, Table 3-2, of the three LULC categories used previously in this dissertation indicated a negative, triangular correlation between urban, agricultural and natural landscapes across 936 non-ocean subwatersheds of New Jersey. Urban areas strongly negatively varied with natural land cover, while agricultural areas were negatively correlated with both urban and natural land covers, though not as highly. Significance of the results is demonstrated by all P-values much less than 0.0001. As shown in the methods section, the percent of watershed in urban, natural and agriculture LULC in each HUC14 subwatershed is indicated in Figures 3-2, 3-3, and 3-4, respectively.

This study also examined the relationship between impervious surface cover and areas mapped as urban landscape at different scales. The urban-impervious correlation cited in previous studies (e.g., Arnold and Gibbons 1996, and Utz et al. 2009) was confirmed at both the mesoscale watershed level by Spearman Rank Correlation across New Jersey's 20 Watershed Management Areas, and by Spearman Rank Correlation of impervious surface as a percent of subwatershed area and urban land cover as a percent of subwatershed area for 233 HUC14s in WMAs 1, 6, and 17, see Figure 3-5. These correlations are considered quite robust as LULC data available from the NJDEP Bureau of GIS is parcel mapped from high-resolution color-infrared orthophotography, collected approximately every five years (NJDEP 2014). Spearman Rank correlations for both data sets described above, subwatersheds (n=233) and WMAs (n=20) were 0.942 and 0.962, respectively. Both correlations were significant and had P-values less than 0.0001.

Relying on the observations of correlation above, further research can benefit from the use of either impervious cover data or urban land cover, based on the availability for the scale and study area of interest.

3.3.2 Spatial analysis of key watershed characteristics

Using WMA 6, six spatial weighting strategies were developed and tested: first order queen contiguity, simple second order queen contiguity, cumulative second order queen contiguity, and three different distance-weighted matrices (3, 5, and 10 miles). The software package GeoDa, developed by Anselin (2005), was used to investigate and model spatial autocorrelation among watershed characteristics and watershed impairment. Because GeoDa does not have the ability to directly process binary response data, the logit transforms of the probabilities calculated in JMP were used to represent the watershed impairment response (dependent) variable.

3.3.2.1 Spatial weight matrix

A first-order examination of the spatial weight matrix connectivity distribution may reveal features of the spatial weights distribution that can affect tests of spatial dependence (Anselin 2005, p. 110). The 5-mile distance weighted connectivity histogram is presented in Figure 3-6 illustrates a bimodal, or clustered connectivity. This non-normal type distribution, though not uncommon in geographic data sets, could create convergence or other issues when calculating measures of spatial autocorrelation and spatial-based regression. Connectivity histograms for the other spatial weight strategies tested can be found in Appendix B.

3.3.2.2 Global Moran's *I*

The global Moran's *I* statistic represents the degree of spatial autocorrelation, and is indicated on the scatter plot of local Moran's *I* as the slope of the line through a plot of standard deviations of the variable of interest on the x-axis and the spatial lag of that same variable on the y-axis (Anselin 1995). Figure 3-7 and Figure 3-8 provide scatterplots of the global Moran's *I* results for the proportion of urban cover in the cumulative drainage area and the urban number, respectively, for each subwatershed in WMA 6. The graph indicates the spatial lag (measured in standard deviations) for each point on the scatter plot (i.e., for each subwatershed). Subwatersheds with low values for the given variable and where the spatial lag is also low (quadrant III), or where the values are both high (quadrant I) are considered to be positively spatially autocorrelated. Locations where the spatial lag and the variable have opposite directions (quadrants II and IV) are said to exhibit negative spatial autocorrelation. The outliers (>2 standard deviations) in Figure 3-8 represent the most downstream subwatersheds, in other words, the subwatersheds with the largest cumulative drainage area. The interpretation made here is that they are not statistical outliers, but rather that they are more spatially lagged because they exhibit a much higher value (i.e., larger drainage area) than most of the other subwatersheds in the data set.

Results of the global Moran's *I* calculations are shown in Table 3-3. The results in Table 3-3 indicate statistically significant positive spatial autocorrelation for the explanatory variables as well as the response variable. The second order queen contiguity weighting strategy generally yielded less significant results and much lower values of the statistic *I*. It is also clear from Table 3-3 that somewhere between 5- and 10-mile contiguity there is a significant drop in spatial correlation between watersheds for all variables. This research suggests that a decrease in spatial correlation occurs between the 5-mile and 10-mile distance weighting because that is the average size of a HUC14 watershed. This finding is consistent with the decrease in significant spatial correlation using second-order queen contiguity, again because the correlation does not extend far beyond the adjacent watershed.

3.3.2.3 Local indicators of spatial association (LISA)

This study also examined clustering and spatial outliers among land use and water quality parameters using techniques for local indicators of spatial association (LISA) developed by Anselin (1995). Since the standard queen contiguity spatial weight matrix strategy was shown to provide the best fit for the global Moran's *I*, the queen weights matrix was the matrix of spatial weights used for the LISA (Local Index of Spatial Autocorrelation) analysis.

As suggested by Yu and Wei (2007), the local Moran's *I* was used to explore local spatial autocorrelation among watershed variables in WMA 6. Table 3-4 shows the results of the univariate LISA analysis, using the GeoDa software. Again, each variable's fit between itself and its spatial lag is significant after a Monte Carlo-type iteration of 9,999 permutations of calculating the Moran's *I* to develop a reference distribution. Because the local Moran's *I* indicates local spatial autocorrelation, a map showing areas of WMA 6 that exhibit significant spatial autocorrelation was developed from the calculations.

The significance levels indicated in the LISA map correspond to the number of permutations used to develop the distribution, and so are not P-values in the classic statistical sense, but they do represent what Anselin (2005) calls "pseudo significance levels" as the larger the number of random permutations, the greater the confidence in the inference. Figure 3-9 presents a LISA significance map for the proportion of urban land in the cumulative drainage basin for each subwatershed, including the significance level.

In addition to the significance map, one should also look at the LISA cluster map for the same variable. Figure 3-10 shows clusters of HUC14s where there is positive (high-high or low-low) spatial autocorrelation for the proportion of urban land. This cluster map matches well with the expectation that areas of high-high positive spatial autocorrelation are areas of urban development, such as Morristown, Parsippany, Florham Park, and Hanover, New Jersey. The areas indicated as low-low correspond to rural and forested areas of northern Morris County and Sussex County. LISA significance and cluster maps for probability of impairment, cumulative drainage area, proportion of agricultural LULC, proportion of impervious cover, and urban number, U_N, are provided in Appendix C.

3.3.2.4 Spatial regression

Significant spatial autocorrelation among the variables representing watershed characteristics that impact stream quality in northern New Jersey exists. To determine if the spatial autocorrelation may be influencing the results obtained by non-spatial logistic regression, an ordinary least squares (OLS) regression was performed. In addition, diagnostics for spatial dependence utilizing the regression functionality in the GeoDa software were determined.

Again, because GeoDa does not have the ability to regress nominal response variables, the data were transformed using the logit for probabilities function from the

JMP analytical suite. Table 3-5 shows the results from the OLS regression of the logit transformed probabilities of impairment with the cumulative drainage area, proportion of urban land, the dimensionless U_N, and proportion of impervious surface as explanatory variables. First, it is evident from the results in Table 3-5 that the largest amount of variation between watersheds for probability of impaired status is explained by the amount of cumulative drainage area contributing to the watershed. In other words, subwatersheds that are further downstream are more likely to be impaired.

Additionally, the study showed that urban land cover and impervious cover have similar explanatory power for watershed impairment, see Figure 3-5. This was expected from the earlier finding that the two characteristics are highly correlated, and supports the findings of previous literature (e.g., Anderson and Gibbons 1996). Urban number was not found to be a significant predictor of watershed impairment. Table 3-5 also includes diagnostics for spatial dependence based on Anselin (2005). Specifically, the global Moran's *I* shows moderate spatial autocorrelation for the variables tested. Lagrange multiplier test statistics (LM) are based on chi-square distributions with one degree of freedom and were used to guide the spatial model specification. The two components calculated by GeoDa are for spatial lag alternative model and spatial error alternative model. The robust forms of the Lagrange multiplier statistics are not considered unless the standard forms are significant (prob.<0.05). The results in Table 3-5 indicate that the LM for the regressions conducted were not significant, except for impervious cover, LM-error. This result shows that there is little spatial dependence among the data tested and the fit of the OLS model will not be improved by an alternative model that includes spatial dependence terms.

Since the LM-error statistic was barely significant, probability <0.045, an alternative spatial error model was conducted. The appropriate estimators of fit for the spatial error model are the Akaike Information Criterion (AIC), log likelihood, and Schwarz criterion (Anselin 2005). Since changes in these three criteria between models tend to correlate, only the AIC is shown in Table 3-6, with the results of the spatial error regression model. The slight improvement in the AIC, smaller indicates better model fit, and the significance of the spatial autoregressive coefficient, λ, indicate that the spatial error model is significant in this case. Additionally, GeoDa provides results for the Breusch-Pagan test for heteroskedasticity, and the likelihood ratio test for the spatial autoregressive coefficient. The Breusch-Pagan test indicated no significant heteroskedasticity, and the likelihood ratio was significant at $p<0.037$ indicating a small chance of model misspecification or simply reflecting the very slight significance for impervious surface in the subwatersheds of WMA 6. These results indicate that spatial dependence of the impervious cover value appears to explain some slight additional variance of the probability that a subwatershed is impaired

3.4 Conclusions

The adoption of watershed-based water quality assessment has introduced potential for both misinterpretation and opportunity by redefining the spatial extent of assessment units for water quality monitoring under the requirements of the Clean Water Act.

Perhaps the biggest advantage of watershed-based assessments for monitoring water quality under the CWA is the implication and realization that all the land in a watershed, and the activities that take place in that landscape, have the potential to impact the ecosystems reliant on the streams and rivers that drain those lands. If data to support the assessments were systematically collected on a watershed basis, then the watershed-based approach could lead to a much improved, science-based, water and ecosystem monitoring and management framework. The results of this study indicate that data collection strategies have not yet caught up to the watershed-based paradigm. The analysis of data that is available does not support a full understanding of the relationship between land-based characteristics and water quality.

Additionally, as geographic information science advances, the ability to apply GIS technology and GIS-based data analysis to watershed management increases. Use of these GIS tools in this study indicates the potential to increase the efficiency and effectiveness of watershed management. While not explicitly studied as part of this investigation, the web-based, open-access availability of GIS-based databases of environmental data used in this study underscores greater opportunity for public engagement on these issues.

The research presented here confirmed through correlation analysis the tightly coupled nature of land use cover patterns. The examination of impervious cover and urban land cover provides the useful conclusion that either metric, depending on data availability, can serve as a proxy for the potential for the built environment to negatively impact water quality.

The chance for misinterpretation comes from the extrapolation of the point source data to represent all waters in a watershed. This study used LULC and number of dischargers as proxies for extrapolation of point sampling data to an entire watershed. These proxies are justified based on the literature cited showing links between LULC and water quality.

The model specification used the proportion of various land use types (agriculture, urban, and impervious surface) as explanatory variables related to impaired watersheds. Other factors, including cumulative drainage area, and number of wastewater dischargers were also included in the regression analysis. The variables listed above were shown to be highly spatially dependent, as measured by the Moran's *I* statistic. As the final result indicated that the spatial model may be misspecified, additional research is recommended to better fit the relationship between watershed characteristics and the likelihood that impaired water quality or ecological indicators will result in a regulatory listing for a watershed-based assessment unit.

This research expressly shows that watershed management can be improved in two important ways. First, a model that includes the effects of spatial dependence may provide a clearer understanding of the link between land use and sources of contamination (especially nonpoint sources) causing impairments. Second, a spatially infused model may provide a statistically valid (and less costly) approach for watershed-based assessment and monitoring of surface water quality.

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Figure 3-1. Land use and hydrography of subwatersheds in Watershed Management Area 6.

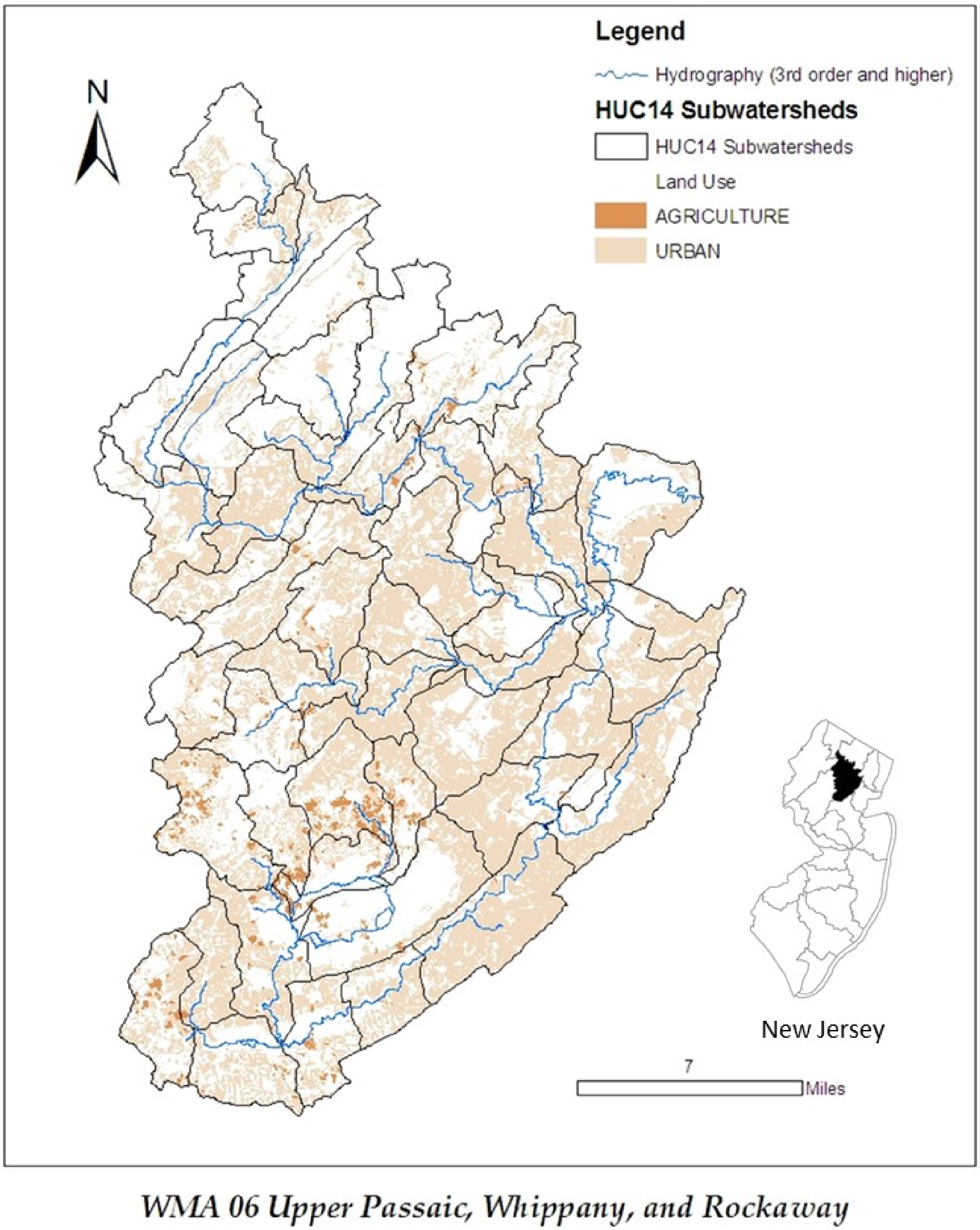

Figure 3-2. Choropleth map of urban land cover in New Jersey subwatersheds.

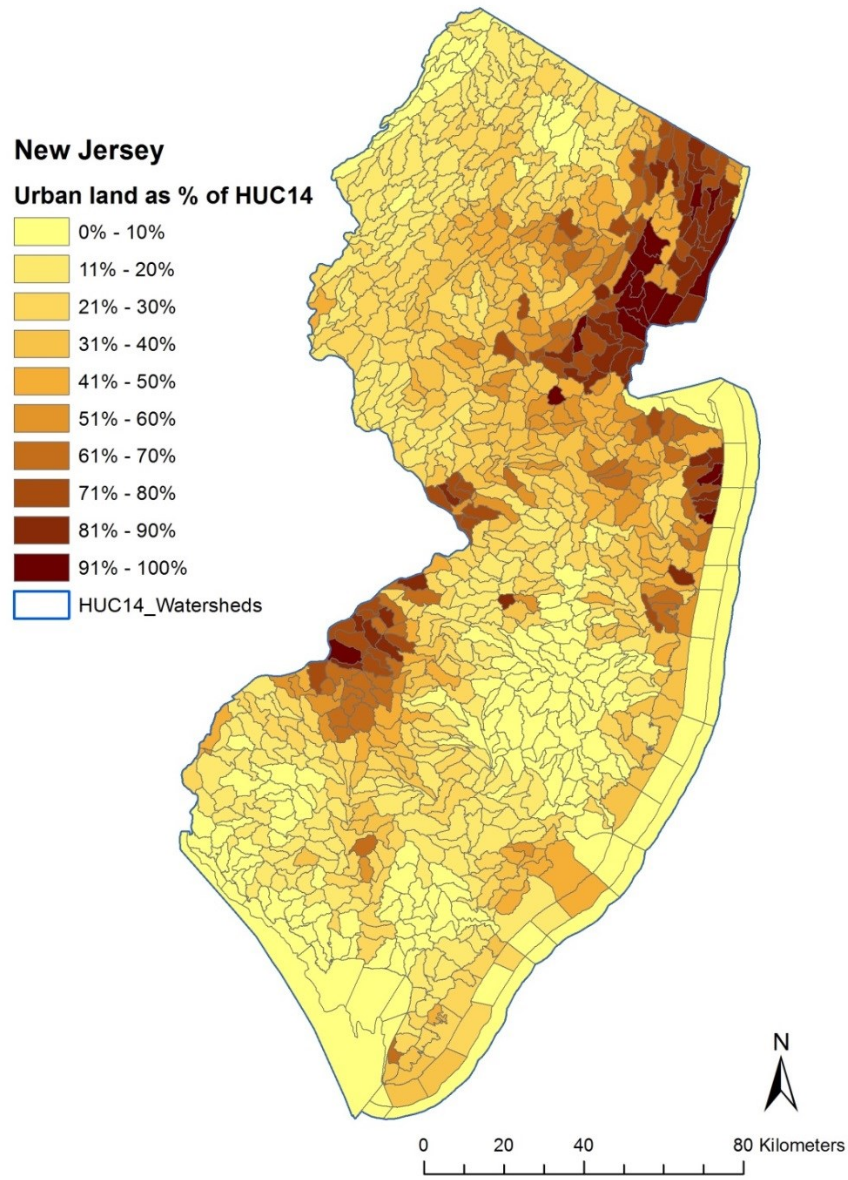

Figure 3-3. Choropleth map of natural land cover in New Jersey subwatersheds.

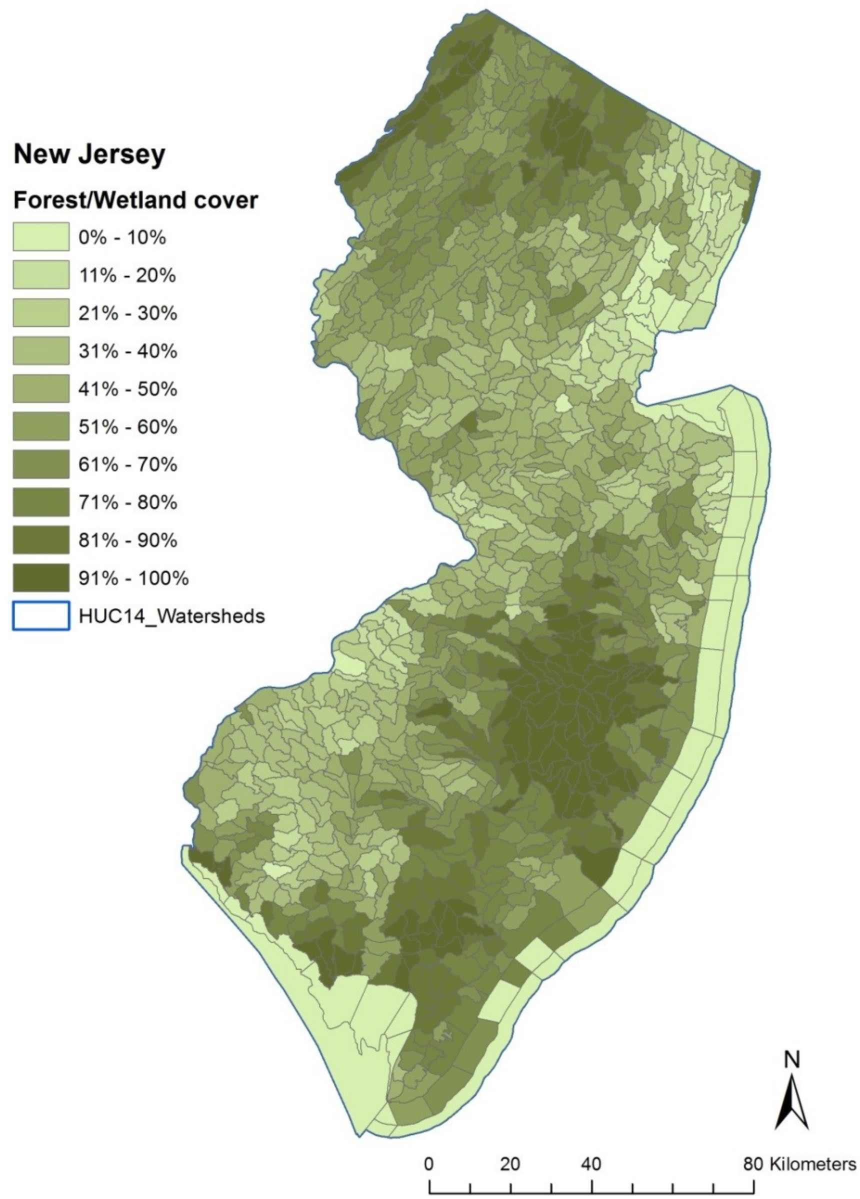

Figure 3-4. Choropleth map of agricultural land cover in New Jersey subwatersheds.

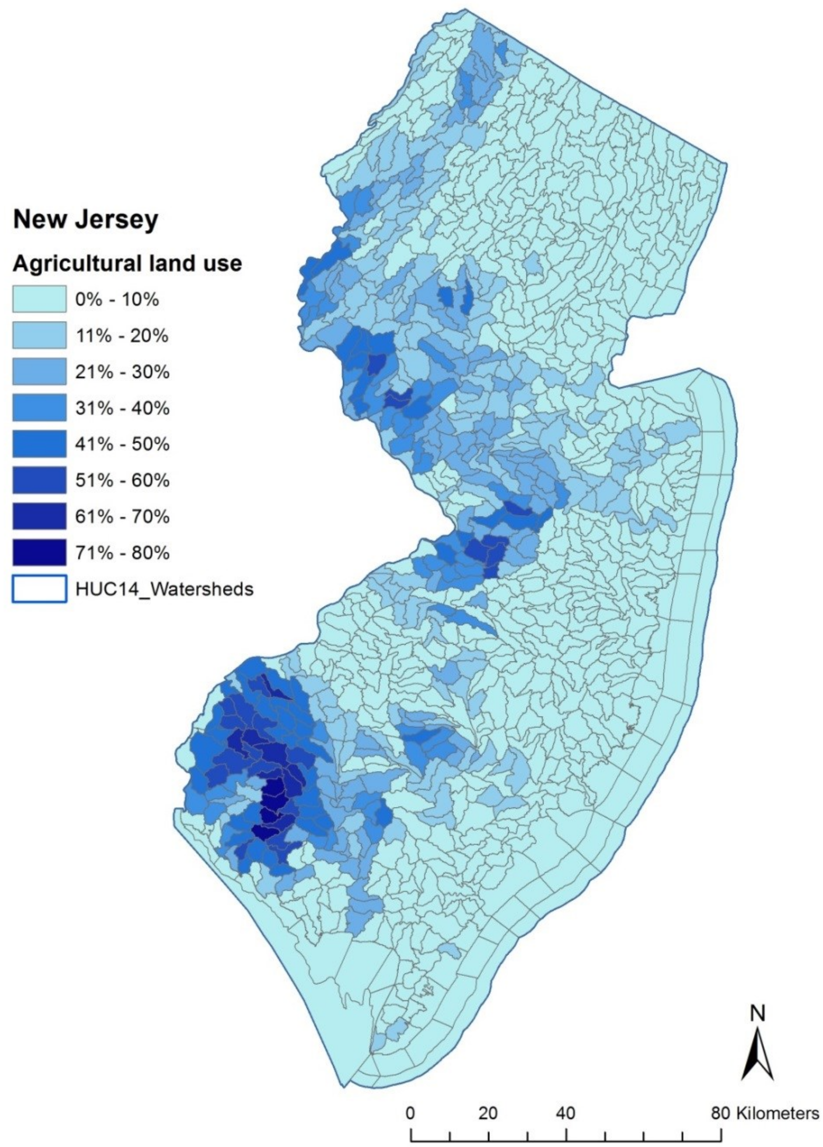

Figure 3-5. Location map for New Jersey watershed management areas 1, 6, and 17.

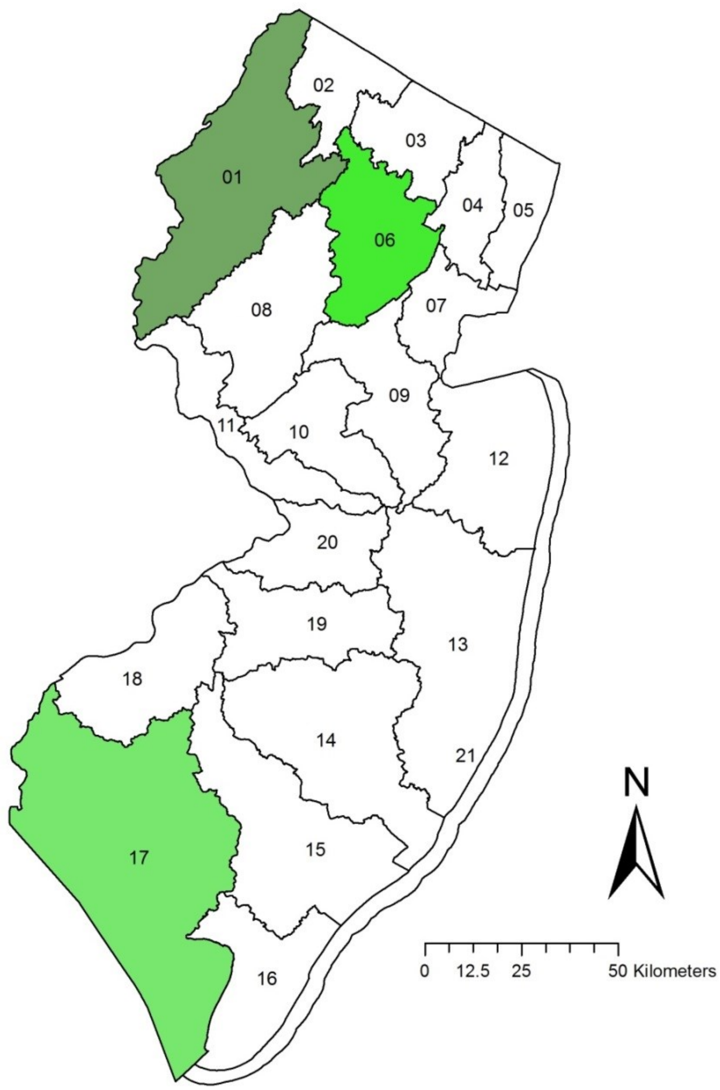

Figure 3-6. WMA 6 subwatersheds: 5-mile distance-weighted connectivity histogram.

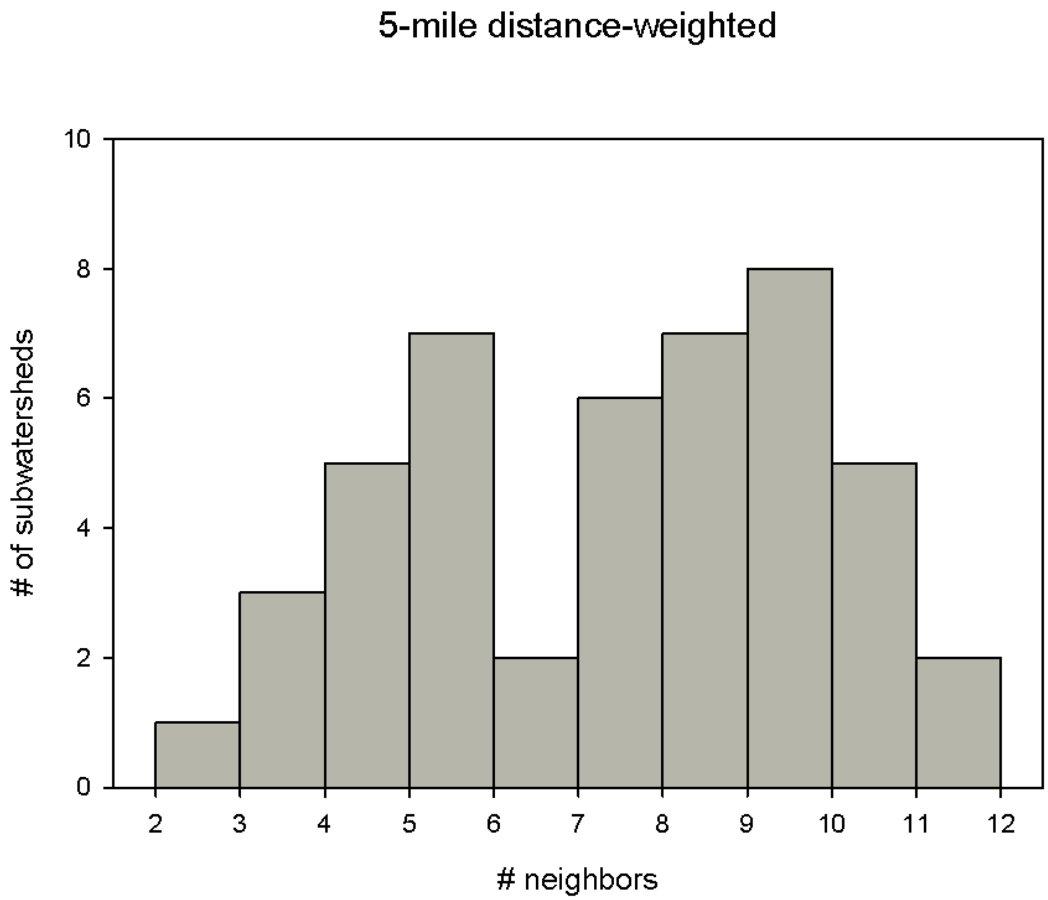

Figure 3-7. Global Moran's *I* scatterplot for proportion of urban land cover in the cumulative drainage for each subwatershed in WMA 6.

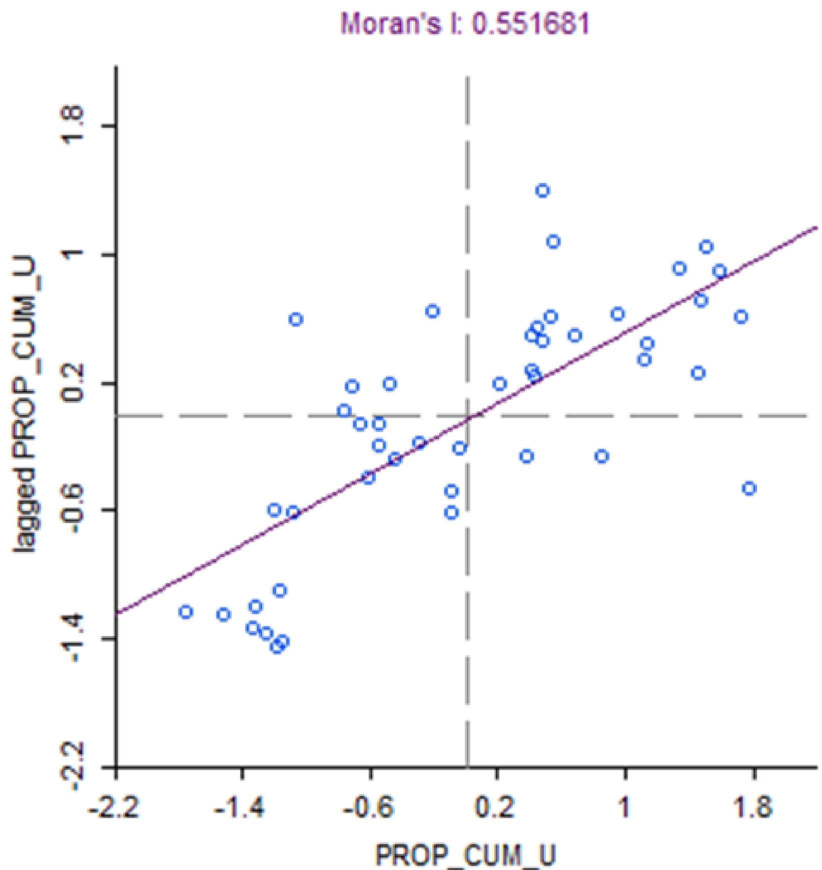

Figure 3-8. Global Moran's *I* scatterplot for urban number, U_N (x100) for each subwatershed in WMA 6.

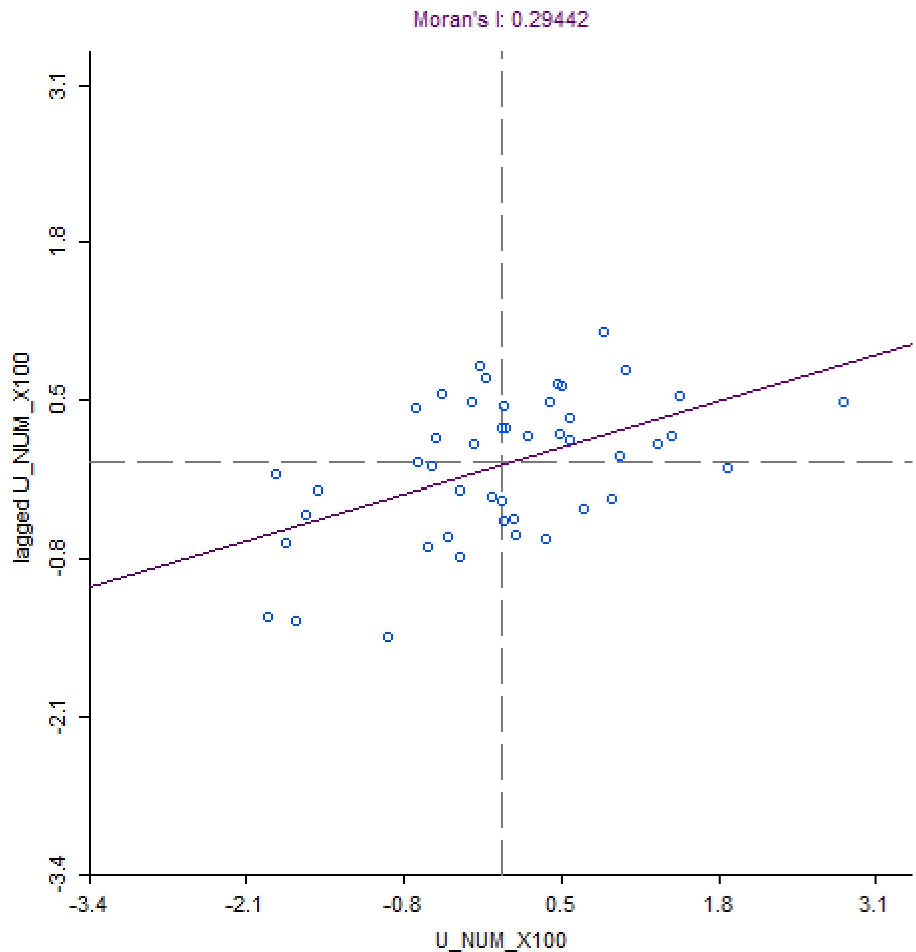

Figure 3-9. LISA significance map for percent urban land cover in subwatersheds of WMA 6.

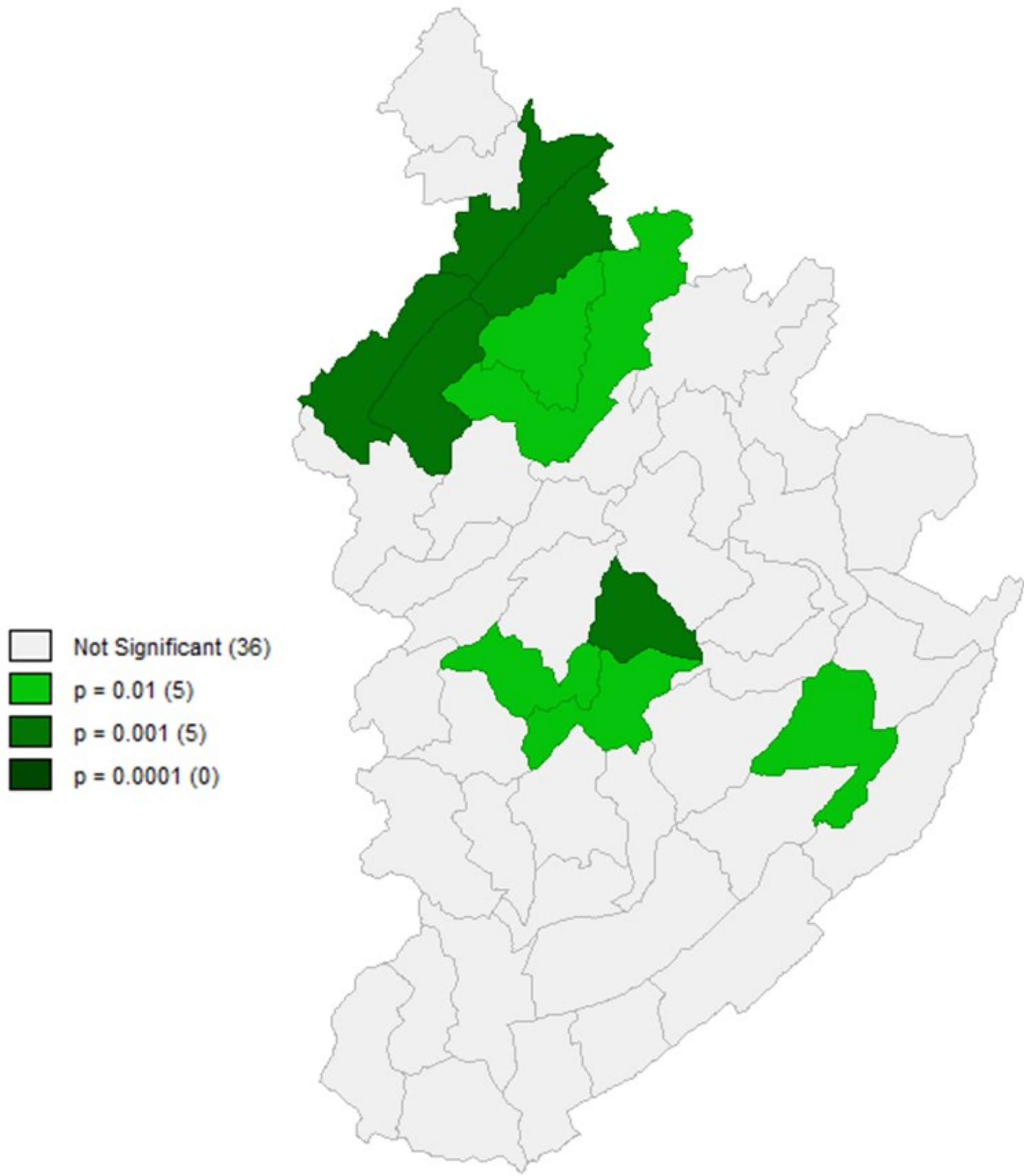

Figure 3-10. LISA cluster map for percent urban land cover in subwatersheds of WMA 6.

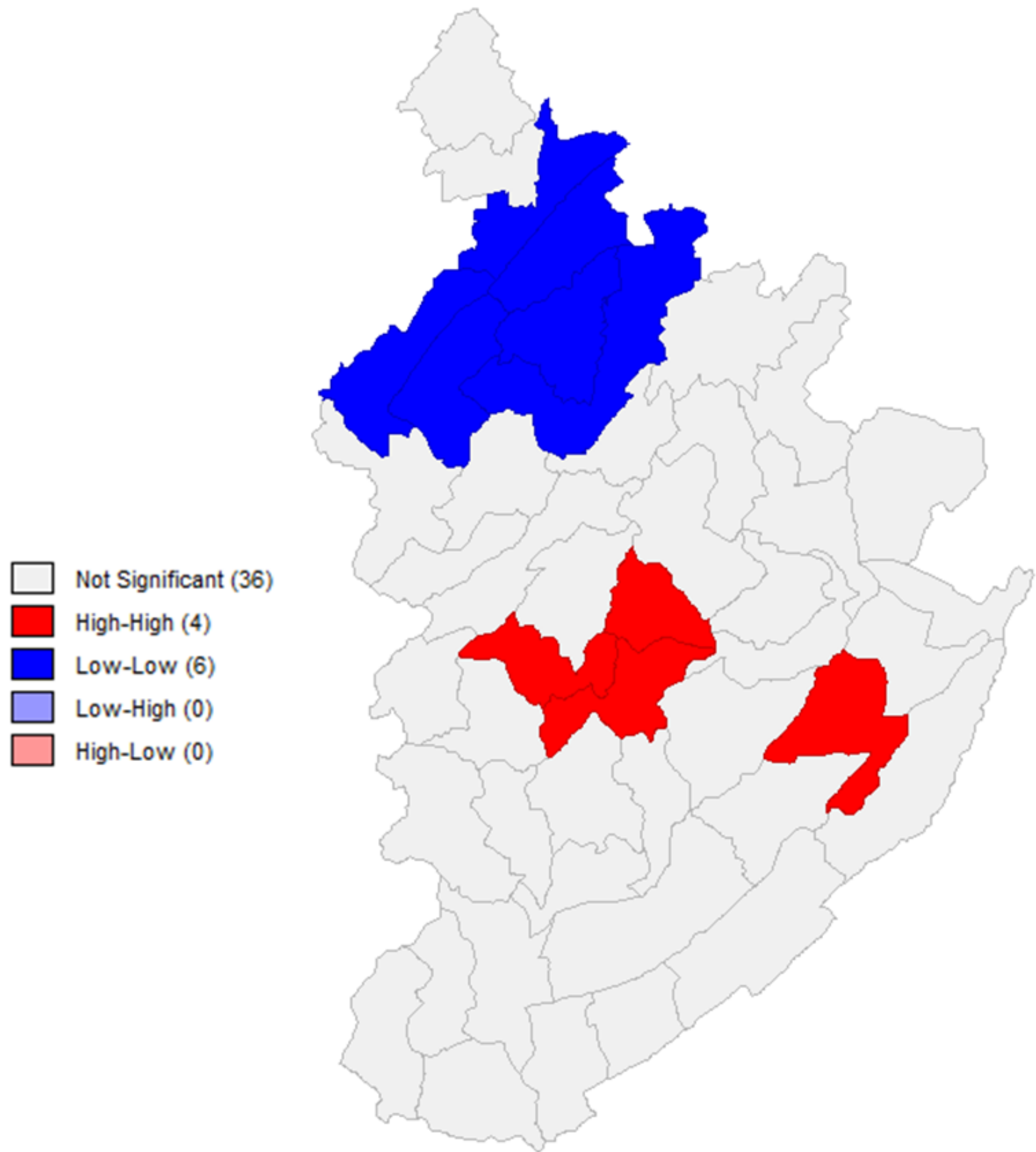

Table 3-1. WMA 6 watershed characteristics.

Water Quality Assessment Unit (HUC14 subwatershed)	Assessment Unit Name	Impaired (1=yes, 0=no)	Cumulative Drainage Area (hectares)	Agriculture (% drainage area)	Urban (% drainage area)	Natural (% drainage area)	Landscape L_D	Urban Number U_N	Impervious Cover (% drainage area)
02030103010010	Passaic R Upr (above Osborn Mills)	0	2,627	7.5%	39.8%	51.8%	Natural	0.151	9.4%
02030103010020	Primrose Brook	0	1,358	6.5%	29.5%	63.3%	Natural	0.128	7.7%
02030103010030	Great Brook (above Green Village Rd)	0	2,054	12.8%	47.7%	38.5%	Mixed	0.194	20.7%
02030103010040	Loantaka Brook	NA	1,311	6.4%	51.5%	41.3%	Urban	0.134	19.0%
02030103010050	Great Brook (below Green Village Rd)	1	6,059	9.3%	38.5%	51.2%	Natural	0.07	12.9%
02030103010060	Black Brook (Great Swamp NWR)	1	3,681	2.6%	26.2%	70.1%	Natural	0.053	11.0%
02030103010070	Passaic R Upr (Dead R to Osborn Mills)	1	14,673	6.5%	37.4%	55.0%	Natural	0.145	10.3%
02030103010080	Dead River (above Harrisons Brook)	1	1,970	7.5%	44.3%	47.7%	Mixed	0.168	13.7%
02030103010090	Harrisons Brook	0	1,412	1.5%	73.3%	24.8%	Urban	0.209	23.3%
02030103010100	Dead River (below Harrisons Brook)	1	5,386	3.9%	52.2%	43.4%	Urban	0.146	11.1%
02030103010110	Passaic R Upr (Plainfield Rd to Dead R)	1	21,792	5.6%	41.0%	52.4%	Natural	0.15	14.1%
02030103010120	Passaic R Upr (Snyder to Plainfield Rd)	1	23,198	5.3%	41.8%	52.0%	Natural	0.146	14.6%
02030103010130	Passaic R Upr (40d 45m to Snyder Ave)	1	26,422	4.7%	46.4%	48.0%	Mixed	0.163	17.4%
02030103010140	Canoe Brook	0	3,115	0.1%	62.6%	32.8%	Urban	0.118	26.6%
02030103010150	Passaic R Upr (Columbia Rd to 40d 45m)	1	31,717	3.9%	49.3%	45.4%	Mixed	0.141	19.8%
02030103010160	Passaic R Upr (HanoverRR to ColumbiaRd)	1	33,936	3.7%	50.0%	44.8%	Urban	0.147	20.8%
02030103010170	Passaic R Upr (Rockaway to Hanover RR)	1	35,723	3.5%	50.4%	44.6%	Urban	0.145	22.1%
02030103010180	Passaic R Upr (Pine Bk br to Rockaway)	1	90,619	1.9%	45.6%	49.5%	Mixed	0.179	21.8%
02030103040010	Passaic R Upr (Pompton R to Pine Bk)	1	93,697	1.8%	45.3%	49.9%	Mixed	0.117	15.3%
02030103020010	Whippany R (above road at 74d 33m)	1	1,570	1.4%	36.9%	60.1%	Natural	0.121	14.2%
02030103020020	Whippany R (Wash. Valley Rd to 74d 33m)	1	3,196	2.3%	33.2%	63.4%	Natural	0.17	31.6%
02030103020030	Greystone / Watnong Mtn tribs	0	2,014	2.4%	55.3%	41.6%	Urban	0.165	25.7%
02030103020040	Whippany R(Lk Pocahontas to Wash Val Rd)	1	6,665	2.0%	46.4%	50.5%	Natural	0.285	30.8%
02030103020050	Whippany R (Malapardis to Lk Pocahontas)	1	8,409	1.8%	51.8%	45.2%	Urban	0.187	47.5%
02030103020060	Malapardis Brook	0	1,319	0.1%	68.1%	30.2%	Urban	0.173	34.6%
02030103020070	Black Brook (Hanover)	NA	2,691	0.0%	66.7%	32.6%	Urban	0.215	38.4%
02030103020080	Troy Brook (above Reynolds Ave)	NA	2,608	0.1%	66.8%	27.0%	Urban	0.136	32.8%
02030103020090	Troy Brook (below Reynolds Ave)	NA	4,175	0.1%	54.8%	40.8%	Urban	0.218	34.1%
02030103020100	Whippany R (Rockaway R to Malapardis Bk)	1	18,050	0.9%	57.1%	40.2%	Urban	0.123	3.6%
02030103030010	Russia Brook (above Milton)	0	2,219	0.0%	16.6%	81.1%	Natural	0.115	5.7%
02030103030020	Russia Brook (below Milton)	0	3,474	0.7%	20.9%	76.0%	Natural	0.099	6.6%
02030103030030	Rockaway R (above Longwood Lake outlet)	1	5,211	0.6%	23.7%	72.6%	Natural	0.057	5.9%
02030103030040	Rockaway R (Stephens Bk to Longwood Lk)	1	7,277	0.5%	20.3%	76.7%	Natural	0.05	2.9%
02030103030050	Green Pond Brook (above Bumt Meadow Bk)	0	1,912	0.4%	11.3%	71.7%	Natural	0.128	9.7%
02030103030060	Green Pond Brook (below Burnt Meadow Bk)	1	3,960	0.2%	21.2%	68.8%	Natural	0.173	9.8%
02030103030070	Rockaway R (74d 33m 30s to Stephens Bk)	1	13,596	0.4%	25.8%	69.5%	Natural	0.196	25.4%
02030103030080	Mill Brook (Morris Co)	0	1,268	0.9%	50.0%	48.9%	Urban	0.238	14.5%
02030103030090	Rockaway R (BM 534 brdg to 74d 33m 30s)	1	16,764	0.4%	32.5%	63.4%	Natural	0.061	8.8%
02030103030100	Hibernia Brook	0	2,055	0.1%	15.9%	82.6%	Natural	0.065	8.8%
02030103030110	Beaver Brook (Morris County)	1	5,884	0.2%	20.3%	72.1%	Natural	0.139	25.7%
02030103030120	Den Brook	0	2,337	1.4%	52.0%	41.4%	Urban	0.111	5.2%
02030103030130	Stony Brook (Boonton)	1	3,185	2.2%	21.6%	71.6%	Natural	0.156	14.5%
02030103030140	Rockaway R (Stony Brook to BM 534 brdg)	1	26,354	0.6%	32.2%	62.4%	Natural	0.169	14.1%
02030103030150	Rockaway R (Boonton dam to Stony Brook)	1	31,328	0.7%	31.5%	62.1%	Natural	0.19	14.3%
02030103030160	Montville tribs.	0	2,052	0.4%	44.1%	53.0%	Natural	0.133	10.0%
02030103030170	Rockaway R (Passaic R to Boonton dam)	1	53,511	0.8%	42.0%	53.1%	Natural	0.11	21.7%

indicates subwatersheds with insufficient data to determine impairment status

Table 3-2. Pearson product moment correlation matrix for land use type.

	Land Cover		
	Urban	Natural	Agricultural
Land cover			
Urban	—		
Natural	-0.785**	—	
Agricultural	-0.328**	-0.328**	—

Note: land cover percentages from 2002 LULC GIS data layer (NJDEP 2014)

*** P ≤ 0.0001*

Table 3-3. Global Univariate Moran's *I* results for WMA 6 (*n=46*).

	Weighting strategy					
Variable	**Queen 1st order**	**Queen 2nd order**	**Queen 2nd order cumulative**	**Dist. 3-mile**	**Dist. 5-mile**	**Dist. 10-mile**
Probability of impairment (as logit)						
I	0.4099	0.0765	0.1893	0.5043	0.4091	0.1212
E[I]	-0.0222	-0.0222	-0.0222	-0.0222	-0.0222	-0.0222
Mean	-0.0202	-0.0236	-0.0241	-0.026	-0.0242	-0.0227
Sd	0.0885	0.067	0.0487	0.1283	0.0704	0.0295
*p-value**	***0.002***	0.073	***0.003***	***0.003***	***0.001***	***0.002***
Cumulative acres						
I	0.4099	0.0765	0.4099	0.5043	0.4091	0.1212
E[I]	-0.0222	-0.0222	-0.0222	-0.0222	-0.0222	-0.0222
Mean	-0.0257	-0.0214	-0.0263	-0.0153	-0.0212	-0.0226
Sd	0.0841	0.0639	0.0851	0.1315	0.07	0.0302
*p-value**	***0.002***	0.068	***0.001***	***0.004***	***0.001***	***0.002***
Cumulative Ag proportion						
I	0.5505	0.3806	0.5505	0.6803	0.526	0.3608
E[I]	-0.0222	-0.0222	-0.0222	-0.0222	-0.0222	-0.0222
Mean	-0.025	-0.0178	-0.0237	-0.0254	-0.0229	-0.0215
Sd	0.0929	0.0706	0.092	0.1411	0.0755	0.0318
*p-value**	***0.001***	***0.001***	***0.001***	***0.001***	***0.001***	***0.001***
Cumulative urban proportion						
I	0.5517	0.3132	0.407	0.5567	0.5469	0.2342
E[I]	-0.0222	-0.0222	-0.0222	-0.0222	-0.0222	-0.0222
Mean	-0.0241	-0.0226	-0.0228	-0.0105	-0.0251	-0.0228
Sd	0.097	0.0735	0.0547	0.1498	0.0787	0.0314
*p-value**	***0.001***	***0.001***	***0.001***	***0.001***	***0.001***	***0.001***
Cumulative impervious proportion						
I	0.5979	0.2367	0.3669	0.6596	0.5538	0.1654
E[I]	-0.0222	-0.0222	-0.0222	-0.0222	-0.0222	-0.0222
Mean	-0.0225	-0.0231	-0.0237	-0.0188	-0.0235	-0.0243
Sd	0.0956	0.0717	0.0546	0.1435	0.0772	0.0293
*p-value**	***0.001***	***0.002***	***0.001***	***0.001***	***0.001***	***0.001***

*p-values are pseudo significance at 999 random permutations

Table 3-4. LISA Univariate Moran's *I* results for WMA 6 (*n=46*).

Variable	Weighting strategy Queen 1st order
Probability of impairment (as logit)	
I	0.4099
E[I]	-0.0222
Mean	-0.0211
Sd	0.0889
*p-value**	***0.002***
Cumulative acres	
I	0.4099
E[I]	-0.0222
Mean	-0.0219
Sd	0.0868
*p-value**	***0.002***
Cumulative Ag proportion	
I	0.5505
E[I]	-0.0222
Mean	-0.0228
Sd	0.0943
*p-value**	***0.001***
Cumulative urban proportion	
I	0.5517
E[I]	-0.0222
Mean	-0.0212
Sd	0.0972
*p-value**	***0.001***
Cumulative impervious proportion	
I	0.5979
E[I]	-0.0222
Mean	-0.0217
Sd	0.0907
*p-value**	***0.001***

*p-values are pseudo significance at 9999 random permutations

Table 3-5. Ordinary least squares (OLS) regression models of probability that a subwatershed is impaired, with diagnostics for spatial dependence.

						Diagnostics for spatial dependence		
Model Rank	**Dependent**	**Independent**	**Adj. R^2**	**P-value**	**AIC value**	**Moran's *I***	**LM-lag (probability)** **Robust LM-lag (prob.)**	**LM-error (probability)** **Robust LM-error (prob.)**
1	logit of probability watershed is impaired	Cumulative drainage area	0.52	<0.0001	200	0.1625	0.6630 0.1263	0.1053 0.0289
2	logit of probability watershed is impaired	Impervious cover, as proportion of watershed	0.13	<0.0083	227	0.2011	0.1134 0.1746	0.0450* 0.0670
3	logit of probability watershed is impaired	Urban land cover, as proportion of watershed	0.11	<0.0140	228	0.1853	0.1213 0.3434	0.0647 0.1670

** Lagrange mulitplier slightly significant at <0.05, suggests additional analysis with spatial error model*

Table 3-6. Spatial error model results for impaired subwatersheds and impervious cover.

Dependent	Independent	Spatial autoregressive coefficient λ	Pseudo R^2	spatial-error model AIC value	OLS model AIC value
logit of probability watershed is impaired	Impervious cover, as proportion of watershed	0.437 ($p<0.009$)	0.262	223	227

Chapter 4 Pulsed adaptive management for Total Maximum Daily Load (TMDL) development and watershed management

Abstract

This research provides a critical review of the current process for establishing and implementing total maximum daily loads for waters that are declared impaired by state or USEPA regulators. This study also introduces an extension of adaptive management, pulsed adaptive management. Pulsed adaptive management is a planned strategy to increase planning, monitoring and management decisions based around specific tasks or projects with defined relatively narrow time horizons. The concept is based on similar strategies exclusive to monitoring fisheries stocks. In an effort to highlight the potential effectiveness of pulsed adaptive management, this study includes a case study examining monitoring and assessment leading to a TMDL needs analysis and development of TMDLs in the Upper Passaic River Basin, New Jersey, USA.

4.1 Introduction

Much of the Passaic River and its tributaries are on the Clean Water Act Section 303(d) list for several impairments including: benthic macroinvertebrates, fecal coliform, phosphorous, total suspended solids, total dissolved solids, temperature, dissolved oxygen, and metals. Total maximum daily loads (TMDLs) are designed to represent the amount of a pollutant (from all sources combined) that can be assimilated by a receiving water without exceeding surface water quality standards. The process of establishing a TMDL for a given water body is a pollution accounting and budgeting process, where the amount of pollution is allocated to various contributing sources. Surface water quality standards (SWQS) are the amount (usually expressed as concentration) of a pollutant that will not harm or degrade human or aquatic life, based on a designated use for that water body. Designated uses are supported by a criterion for each parameter of concern. Water quality standards are typically developed by States with guidance from the United States Environmental Protection Agency (USEPA). Therefore, Total Maximum Daily Loads (TMDLs) have been or will soon be determined for many stream segments within the Passaic River watershed (NJDEP 2012). The key to a successful TMDL program is having a sufficient monitoring plan to collect the necessary amount and type of data to support the connection between TMDL implementation and water quality improvement.

Stream restoration activities are supported in New Jersey and across the United States through a combination of funding through the Clean Water Act grant programs, local government initiatives and local nongovernmental organization (NGO) participation. Stream restoration goals typically consist of physical alteration of degraded stream ecosystems through streambank stabilization, engineered wetlands or reconnection to former riparian wetlands, dam removal, import or export of large woody debris (LWD), stream bed alteration to improve riffle and pool morphology. Less common under the stream restoration rubric are socioeconomic mechanisms such as preservation of riparian land, rules and regulations prohibiting disturbance in riparian and wetland areas, and regulatory control of point and nonpoint sources of pollution.

Although adaptive management is often discussed within the TMDL framework, whether as part of a Margin of Safety (MOS) or as a separate implementation tool, it is rarely incorporated in a meaningful way. Pulsed monitoring (Bryant 1995) is an approach to concentrate monitoring activities in time and space. Effective pulsed monitoring is a cost effective strategy that maintains sampling requirements for appropriate capture of temporal and spatial environmental data. In order to reconcile the advantages of adaptive management, this chapter presents the case for "pulsed" management supported by pulsed monitoring for a cost-effective approach to stream restoration.

4.2 Methodology development and information resources

4.2.1 Total Maximum Daily Load (TMDL)

The Federal Clean Water Act (33 U.S.C. 1251 et seq.) or "Clean Water Act" requires states to report on the quality of their waters every two years. These reports must include designated uses for each water body and information about attainment of water quality standards supporting those uses. These reports and lists are named for the section of the Clean Water Act (CWA) where they originate. The two required reports are the Water Quality Inventory Report [305(b) Report] and the List of Water Quality Limited Waters [303(d) List]. The USEPA encourages states to submit this information together in one report known as an Integrated Water Quality Monitoring and Assessment Report. New Jersey last submitted an Integrated Report in 2004. According to the 2004 New Jersey Integrated Water Quality Monitoring and Assessment Report ("Integrated

Report", p. I-1), the 303(d) list identifies "impaired waterbodies: those waters for which technology-based pollution controls were not stringent enough to achieve the state's surface water quality standards." New Jersey is required to propose TMDLs for those impaired waters, based on a priority ranking system. The 305(b) report, on the other hand, provides the water quality status of all waters of the state.

The New Jersey Department of Environmental Protection (NJDEP) states in its Integrated Water Quality Monitoring and Assessment Methods ("Methods Document" 2003, p. 1) that:

> "The Integrated Report is intended to provide an effective tool for maintaining high quality waters and improving the quality of waters that do not attain water quality standards. The Integrated Report also provides water resource managers and citizens with detailed information regarding the following:
>
> • Delineation of water quality assessment units providing geographic display of assessment results;
>
> • Progress toward achieving comprehensive assessment of all waters;
>
> • Water quality standards attainment status;
>
> • Methods used to assess water quality standards attainment status;
>
> • Additional monitoring needs and schedules;
>
> • Pollutants and watersheds requiring Total Maximum Daily Loads (TMDLs);
>
> • Management strategies (including TMDLs) under development to attain water quality standards;
>
> • TMDL development schedules."

4.2.2 Data sources

The Integrated Report and Methods Document helps NJDEP implement science-based decision making in monitoring and assessment of water quality as recommended by the National Research Council (2001). The NJDEP Methods Document states that "The Department reviews all existing and readily available data as required and is committed to using only data with acceptable quality assurance to develop the Integrated Report." To that end the NJDEP (2004) has used data from several sources and organizations to determine the existing state of water quality of New Jersey waters. The data sources and parameters sampled by each are provided as follows:

NJDEP-United States Geological Survey (USGS) Cooperative Ambient Stream Monitoring Network (ASMN),
<u>Parameters</u>: Bacteria were monitored 5 times within 30-days as recommended in the NJSWQS. Conventional water quality parameters (i.e., dissolved oxygen, nutrients, solids, and pH) were monitored at all stations seasonally, 4 times per year. Diurnal DO data were collected at a subset of ASMN stations. Flow is continuously monitored or instantaneous discharge measurements were collected during seasonal monitoring.

USGS National Ambient Water Quality Assessment (NAWQA),
<u>Parameters</u>: dissolved oxygen, nutrients, solids, and pH.

NJDEP Marine and Estuarine Monitoring Program,
<u>Parameters</u>: dissolved oxygen, ammonia-nitrogen, nitrate-nitrite, organic nitrogen, ortho-phosphate, chlorophyll a, Secchi depth, salinity, temperature, pH, suspended solids, fecal and enterococcus bacteria.

Ambient Biological Monitoring Network (AMNET),
<u>Parameters</u>: benthic macroinvertebrate organisms, including crustacean, larval insects, snails and worms.

Warmwater Fisheries Populations,

Parameters: Fish populations were sampled using electrofishing (spring or fall), shoreline seining (summer to assess fish reproduction), and/or gillnetting (fall). Conventional water quality parameters such as dissolved oxygen; pH and nutrients are recorded during the summer months when the water columns are most stratified.

New Jersey Pinelands Commission (NJPC),

Parameters: The NJPC collects biological and chemical/physical data for streams, rivers and impoundments within the Mullica River (Zampella, R.A., et al. 2001) and Rancocas Creek (Zampella, R.A., et al. 2003) watersheds.

Clean Lakes Program,

Parameters: total phosphorus, Secchi disk transparency and chlorophyll a.

USEPA Helicopter Monitoring Program,

Parameters: dissolved oxygen and fecal coliform in near-shore coastal waters.

The Interagency Toxics in Biota Committee,

Parameters: monitoring of fish and shellfish tissue for contaminants of concern to human health. Sampling locations were chosen to include areas where known or suspected sources of persistent bio accumulative toxics (PBTs) might be found (e.g., PCBs, dioxin, pesticides, and mercury).

National Shellfish Sanitation Program,

Parameters: total and fecal coliform bacteria in water and shellfish.

Monmouth County Health Department,

Parameters: pH, fecal coliform, TSS, phosphorus, ammonia, ,and benthic macroinvertebrates.

Hudson Regional Health Commission,

Parameters: fecal coliform.

Interstate Environmental Commission,

Parameters: fecal coliform and dissolved oxygen.

Delaware River Basin Commission (DRBC),
DRBC has the 305(b) Report responsibility for the Delaware River mainstem and estuary. DRBC's 305 (b) Report can be found on their web page at http://www.state.nj.us/drbc
Superfund and RCRA,
on a site-specific basis, where appropriate.

These data combined with readily available stream flow data (USGS) and climate data (e.g., precipitation, air temperature, wind speed, and direction) from the National Oceanic and Atmospheric Administration (NOAA) represent data available to establish reference or baseline conditions at a point in time and for continued assessment of water quality improvement. The NJDEP relies on information from these sources to create the 303(d) list of impaired waters.

4.2.3 Estimating spatial extent

The NJDEP and USGS (NJDEP, 2003) developed a method for estimating the spatial extent of impairment associated with an individual stream monitoring location. The NJDEP (2003) says that "The goal of this spatial extent method is to maximize the use of monitoring data without overestimating the geographical extent the data represents. Estimation of spatial extent is based on hydrology using the widely accepted Strahler stream order system." Strahler's (1952) classification system refers to stream segments rather than entire streams. He defines headwater streams with no tributaries as First-order streams (1^{st} order). A "2^{nd} order stream" is formed at the confluence of two 1^{st} order streams. Stream order changes when two or more streams with the same stream order converge. For example, two 2nd order streams converge to create a 3rd order stream. In the Strahler scheme, stream order does not change if a lower order stream converges with a higher order stream.

Another example, if 2nd or 3rd order streams converge with a 4th order stream, the 4th order stream does not become a 5th order stream but continues as a 4th order stream until it converges with another 4th order or higher stream. Figure 4-1 shows an example diagram of Strahler stream order. Generally, Strahler stream order increases with flow and watershed size; however, there is an inherent idiosyncrasy in the Strahler scheme.

The Strahler scheme does not count the contribution of each tributary entering the system. This inconsistency was addressed in the stream order classification system of Shreve (1967). Shreve indicated that the stream order should increase at each convergence by the value of the two streams added together (see Figure 4-2). For a graphic comparison of the two systems, see Ritter (1978, p.178). Despite Shreve's improved method, many practitioners, including the NJDEP still use Strahler's system. The NJDEP used Strahler stream order, size of the watershed draining to the monitoring site, land use/land cover, impoundments, and station type (for stations in the redesigned ASMN) to determine the upstream and downstream extent of monitoring. NJDEP has recently begun to adopt U.S. Geological Survey (USGS) national hydrography data, which does not use either type of stream order. Watersheds, the new management and assessment unit being implemented by NJDEP, are nested similar to the Shreve method, but using a different naming convention.

According to NJDEP (2004), "monitored waters are reaches immediately adjacent to monitoring sites." These are the stream reaches to which the monitoring station data are attributed, and are used in water quality assessments for sublists 1 through 5 of the CWA Section 303(d) report of impaired waters. The listed impairment status for "estimated waters" are extrapolated from monitoring stations and further supported based on land use. Lastly, "unassessed waters" are waters for which the NJDEP believes there is insufficient data to determine status.

Although the NJDEP considers the available data adequate for listing impaired waters on the 303(d) list, they almost categorically list undefined "targeted studies" as part of the "follow-up monitoring" for proposed TMDLs. This data/management gap will be discussed further in the section on adaptive management.. The majority of the data for streams comes from the ASMN and AMNET data sets. This data set is derived from relatively sparse monitoring locations, but according to NJDEP is adequate for establishing the 303(d) list. A detailed analysis of the magnitude and types of uncertainty associated with using this data for this purpose is recommended but not part of this dissertation.

4.2.4 Ranking and prioritizing impaired waters

Section 303(d) of the CWA requires that states provide a prioritized list of impaired waters [303(d) list]. According to the NJDEP Methods Document (2003), "The goal of priority ranking is to focus available resources on the right waterbodies at the right time, in the most effective and efficient manner, while taking into account environmental, social and political factors." The stated goal above highlights the need for a flexible management system. The NJDEP uses a wide range of information, reproduced below, to prioritize its 303(d) list, but the element given the most weight (NJDEP 2004) is the parameter of concern designation and how it relates to protection of human health. The weighting factors used by NJDEP to rank impaired waterbodies are as follows:

- ♦ Parameter of concern
- ♦ TMDL complexity
- ♦ Status of parameter with respect to actively produced or legacy
- ♦ Additional data and information collection needs
- ♦ Sources of the pollutants
- ♦ Severity of the impairment or threatened impairment
- ♦ Spatial extent of impairment
- ♦ Designated uses of the waterbodies
- ♦ Efficiencies of grouping TMDLs for waterbodies located in the same watershed or for the same parameter of concern
- ♦ Efficiencies related to leveraging water quality studies triggered by NPDES permit renewals.
- ♦ Status of TMDL currently under development
- ♦ Timing of TMDLs for shared waters
- ♦ General watershed management activities (e.g. 319 grant activities and watershed management planning)
- ♦ Other ongoing control actions that will result in the attainment of SWQS (e.g. site remediation activities)
- ♦ Existence of endangered and sensitive aquatic species
- ♦ Recreational, economic, cultural, historic and aesthetic importance
- ♦ Degree of public interest in, and support for, particular waterbodies.

Table 4-1 illustrates how NJDEP uses pollutants of concern to determine qualitative priority ranks for the 303(d) list (NJDEP 2006, 2009 and 2012).

4.3 Results and discussion

As shown in the following case study of the Passaic River Basin, New Jersey, adaptive management and pulsed management in particular can play a crucial role in successfully meeting the water quality goals of the TMDL process. The great benefit of adaptive management strategies is that they address and reduce uncertainty. Walters and Hilborn (1978) describe adaptive management approaches as “a process of learning about system responses through experience.” They describe two types of adaptive management: passive and active. Passive adaptive strategies combine existing studies and previous experience to build a model to describe the past behavior of the system then manage assuming the model will accurately predict future behavior. Active adaptive management assumes that each management decision or action is a “deliberate experiment” that will meet short-term goals and also inform long-term management strategies by providing new data and additional knowledge of the system.

4.3.1 Case study: Passaic River Basin

In the report titled “*Amendment to the Northeast, Upper Raritan, Sussex County and Upper Delaware Water Quality Management Plans: Phase I Passaic River Study Total Maximum Daily Load For Phosphorus in Wanaque Reservoir Northeast Water Region*”, the NJDEP (Phase I Report, 2005) indicates that 17 segments in the Passaic

River basin are impaired for phosphorus based on in-stream concentrations of total phosphorus in excess of the water quality standard of 0.1 mg/l. Of these 17 segments, 12 are ranked as “high” priority in the Integrated Report (NJDEP 2004) and five segments as medium priority. Although these segments of the Passaic River are predominantly in WMA 3 (see Figure 4-3), the implication for WMA 6 is clear. Both watersheds are in the Highlands physiographic province, have similar patterns and density of urban development, and both expect to see significant additional suburban-style development over the next 30 years. Lathrop et al. (2007) estimate that two-thirds of the subwatersheds in the Highlands area, physiographic region for most of WMAs 3 and 6.

In addition, nine stream segments are identified in the Integrated Report as having insufficient data to be fully assessed. Analysis of additional data compiled for the Phase I Report determined that two of these segments are actually not impaired, two are confirmed impaired and five are still unconfirmed. The Wanaque Reservoir, although not listed as impaired, had been identified as a critical location and possible endpoint due to water supply utilities occasionally pumping impaired stream water into the reservoir. In the course of developing the Phase I TMDL, NJDEP determined that the reservoir is impaired, as indicated by phosphorus levels in excess of the standards. Therefore, NJDEP has indicated that the Phase I Report will establish one TMDL for the Wanaque Reservoir. TMDLs for the 19 in-stream impairments will be developed in the Phase II study.

USEPA (Sutfin 2002) provided guidance on the statutory and regulatory requirements for TMDLs to be submitted to USEPA for review and approval. USEPA guidance outlines 11 key areas that are either required by statute, regulation or guidance documents to allow USEPA to support approval of a TMDL (see Table 4-2).

The first two items in the list concern identifying impaired waters and developing water quality standards. These are determined by monitoring data and defined designated uses for a given waterbody. The next five items relate to the modeling exercise that is the quantitative heart of the TMDL process. The assimilative capacity and load allocations, margin of safety, and seasonal variation are parameters that are determined by or part of an iterative modeling system. In the case of TMDLs, the models are mathematical equations that represent a scientific approximation of natural processes. They may be simple or complex depending on the desired result and the available input data. USEPA does not prescribe what models to use or how to run the models for determining a TMDL, but they generally expect states to employ known and tested modeling systems to develop TMDLs. The last four items addressed in the USEPA guidance can mean the difference between a successful TMDL and little or no water quality improvement. Stakeholder involvement, implementation strategy, post-implementation monitoring, and reasonable assurances combine to form the management approach for ensuring the TMDL leads to attainment of designated uses as efficiently and effectively as possible.

Although the NJDEP claims to have addressed these guidance parameters (Phase I Report, p. 5), there is little substance in the report regarding reasonable assurance that the TMDL will be successful and even less about post-TMDL monitoring and how the post-TMDL management and implementation process will adapt if water quality improvement goals are not being met in a reasonable time. Section 6.0 of the Phase I report states, “The ambient networks [ASMN], as well as targeted studies, will be the means to determine the effectiveness of TMDL implementation and the need for additional management strategies.” What “targeted studies” are to be conducted? What “additional management strategies” are available?

Another key element in this nutrient TMDL is the assumption that nonpoint sources can be reduced by 80%. Although wetlands are well known to provide phosphorus removal, most experiments have shown only 50-66% phosphorus reductions. Kadlec and Knight (1996) report on 49 marshes with an average P removal efficiency around 66%, though performance varies widely with season and location. Heyvaert et al. (2006) showed that a constructed wetland for surface stormwater flow reduced median phosphorus levels by almost two-thirds. Additionally, total nitrogen was reduced by about 50% and total suspended solids by about 74%. However, constructed best management practices (BMPs) and natural wetland areas for water quality treatment are not part of the implementation plan for this TMDL. The implementation plan in the Phase I Report instead relies heavily on local behavior modification ordinances, such as pet waste removal, geese-management, and septic management ordinances. These are all good practices to implement and will undoubtedly have the effect of keeping some amount of pollutants out of the waters of the Passaic Basin but will not likely achieve overall 80% reduction of phosphorus loading from all nonpoint sources.

Additionally, assurance that TMDLs will meet stated objectives is given in the report, but not described with any management procedures attached. The public participation process will also under serve the community if the public hearing component remains discretionary. Generally, this study found a lack of detail and planned flexibility in the management aspects of TMDL implementation for the Passaic River Basin TMDL.

4.3.2 Active and pulsed adaptive management

Walters and Holling (1990) describe active adaptive management (AAM) as highly beneficial after policies have been defined, and action needs to be taken. The advantage is that AAM assumes that knowledge of the system in question is incomplete. Walters and Hilborn (1990, p.2067) state that, "Not only is the science incomplete, the system itself is a moving target, evolving because of the impacts of management and the progressive expansion of the scale of human influences on the planet. Hence the actions needed by management must be ones that achieve ever-changing understanding as well as the social goals desired."

The NRC (2001) recommends application of "adaptive implementation" in the TMDL process. Specifically, they suggest initial actions that have little uncertainty regarding the water quality outcome, such as upgrades to waste-water treatment plants or transfer of properties with failing individual septic systems to sanitary sewer systems. The adaptive process begins with future actions, which the NRC says "must be based on (1) continued monitoring of the waterbody to determine how it responds to the actions taken and (2) carefully designed experiments in the watershed." This is certainly a good example of active adaptive management as described by Walter et al. (1978 and 1990), but it may not be acceptable or appropriate given stakeholder feedback and ever-present budget constraints of both government agencies, tasked with oversight of the TMDL process and the regulated community itself. Pulsed adaptive management (PAM), as proposed here, is an approach that can provide the benefits of AAM but with reduced overall expenditures. Based on extrapolation from the USEPA report (USEPA 2001) on TMDL costs, the costs to implement TMDLs in watershed management area 6, another part of the Passaic basin, are significant (see Table 4-3). Typically these costs are incurred by local wastewater utilities (USEPA 2001) and so are ultimately borne by the population served by those utilities.

However, all management alternatives contain trade-offs. PAM may not be able to identify or respond to system changes as rapidly as AAM, but the reduced implementation costs should make it an attractive alternative. PAM is ideally suited to management of the TMDL process, especially where alternative strategies such as water quality trading or natural treatment systems are implemented to meet TMDL requirements.

Adaptive implementation of the TMDL process (NRC 2001) involves several steps including: 1) defining both short-term and long-term actions designed to meet designated uses in a waterbody, 2) conducting monitoring activities and system behavior experiments to support those actions, and 3) a feedback mechanism to refine the TMDL plan and supporting models. See Figure 4-3. PAM is a method to inject reasonable temporal, spatial, and economic milestones into an AAM framework. In addition, PAM can be linked to a decision support tool to optimize a number of objective functions within the TMDL framework. PAM takes advantage of the fact that at any given time there are: 1) impaired waters, as listed and ranked by priority on the 303(d) list; 2) a number of TMDLs in various stages of development (proposed, established, approved, adopted); 3) various monitoring and experimental activities necessary to support the first two items; and 4) limited resources (personnel and financial) to carry out all of the above. These represent the four basic parameters necessary to define a pulsed adaptive management strategy for TMDLs.

Similar to pulsed monitoring (see Bryant 1995), PAM utilizes the concept that all management systems are subject to two continuous variables, intensity and duration. PAM overlays intensity- and duration-derived decision points on the AAM framework. If one pictures AAM as a management structure with built in feedback mechanisms, PAM apportions the intensity and duration of these feedback loops based on the value of the four parameters described above. In other words, PAM would indicate high intensity (many short feedback loops) for management of short-term actions or narrowly focused TMDLs and lower intensity (fewer) feedback loops for management of actions with long-term decision horizons (e.g., behavior modification/education strategies for nonpoint sources).

4.4 Conclusions

The TMDL process in New Jersey is moving forward. Several priority waterbodies (NJDEP 2006, 2012) have proposed TMDLs. These waterbodies were on the 303(d) list based on monitoring data. However, removing waterbodies or subwatersheds from the 303(d) list after a TMDL is approved is misleading. This study recommends the delisting process only be applied to waters that have supporting sampling data. Pulsed management can inform the data collection effort, pulsed monitoring, though use of the TMDL actions and 303(d) lists. The data set may be adequate for purposes of listing stream segments, but it is generally too sparse in most areas to support measurement of the effects of actions required under TMDL implementation plans. Additionally, the NJDEP methodology for extrapolating spatial extent from the monitoring data could be strengthened, but that analysis is beyond the scope of this research. The addition of pulsed monitoring to measure both long-term effectiveness of TMDLs and long-term effectiveness of stream restoration projects is also recommended.

Prior investigators (Walters and Hilborn 1978, Walters and Holling 1990, NRC 2001, Frissell and Ralph 1998) have argued for the use of adaptive management for ecological and water resource management. This research has proposed a form of adaptive management called pulsed adaptive management (PAM) for water quality management. PAM matches adaptive management feedback mechanisms (monitoring and re-examination) with a duration and intensity characteristic fitting the scope and scale of the TMDL. PAM should allow for more focused management of the TMDL process at critical decision points and lower intensity where decision points are more spread out over time or lower priority. Overall, PAM may lower management costs by providing a focused management framework customized for a given TMDL, or even a group of TMDLs.

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Figure 4-1. Strahler stream order (adapted from Strahler 1952).

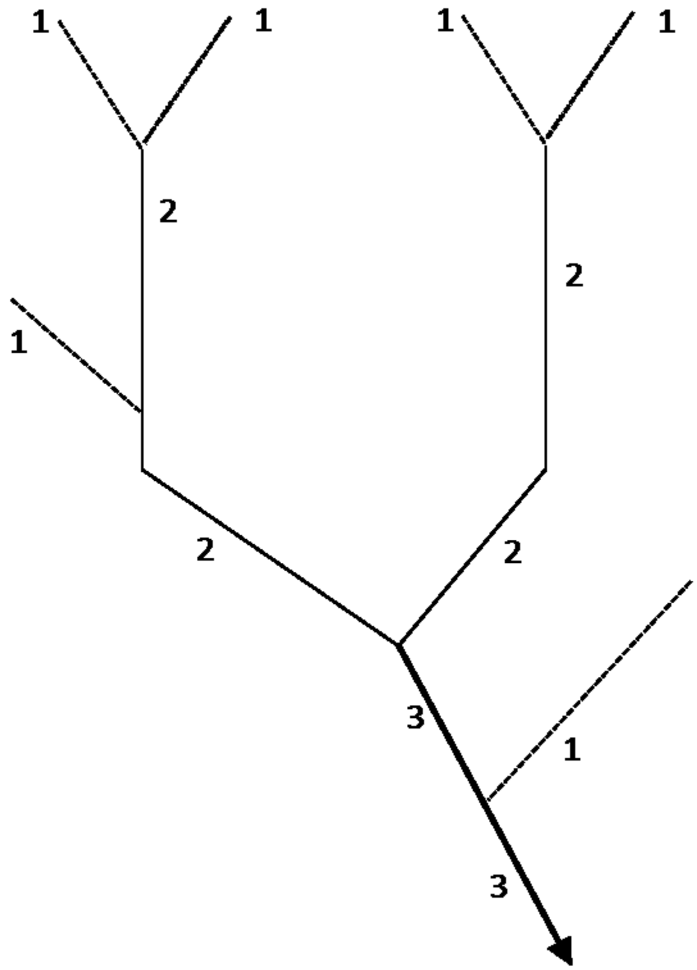

Figure 4-2. Shreve stream order (adapted from Shreve 1967).

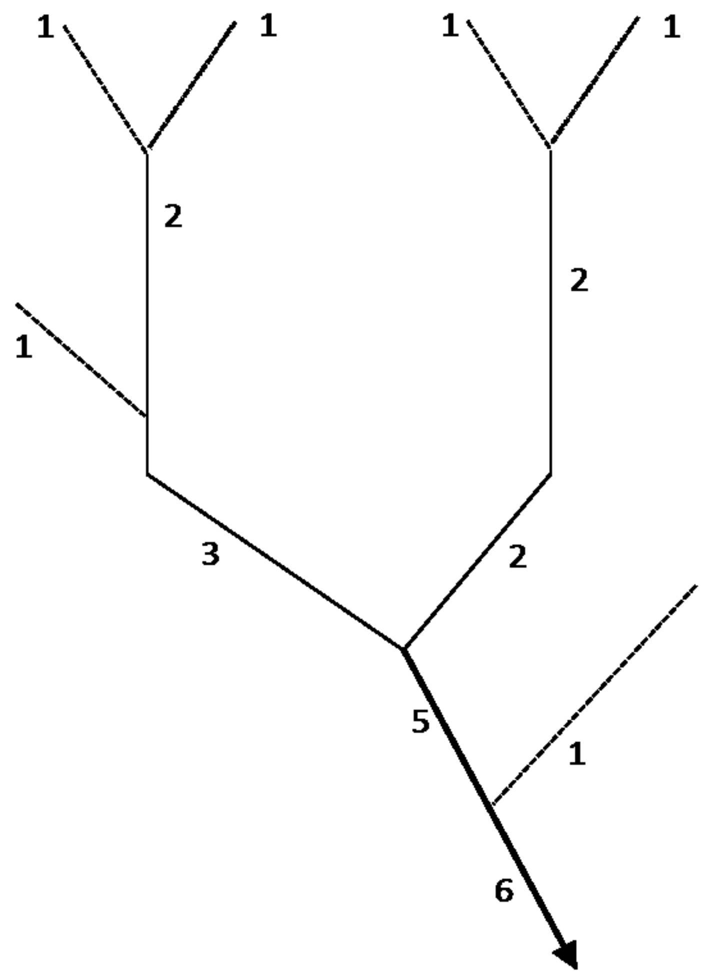

Figure 4-3.	Location map for watershed management areas of New Jersey.

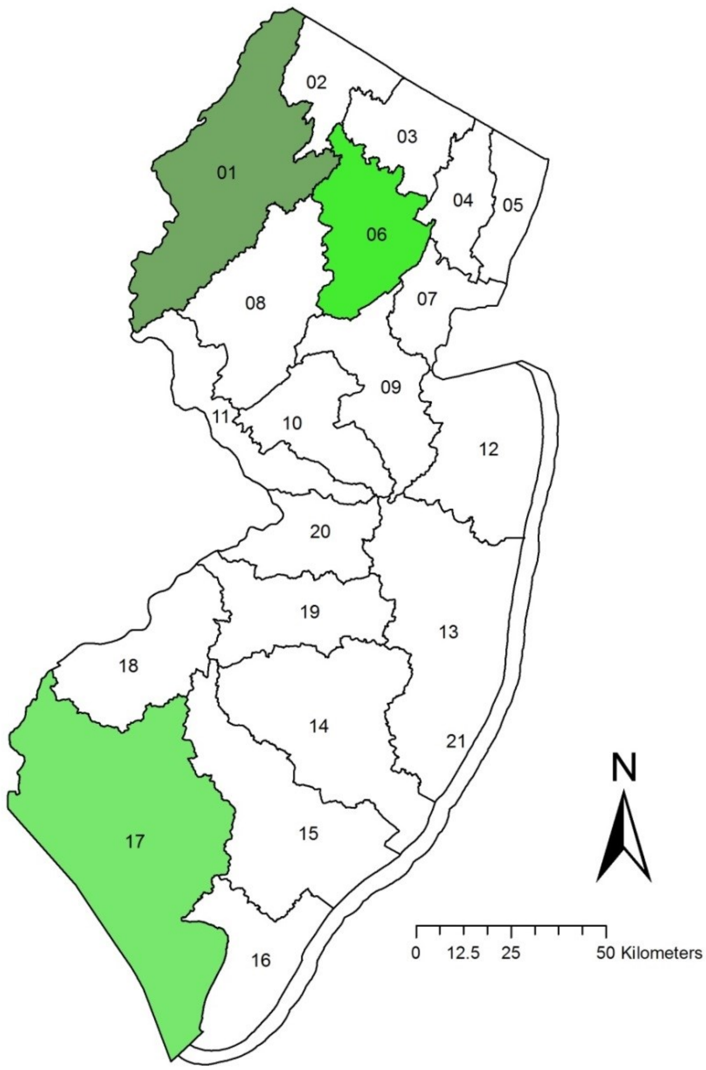

Table 4-1. Priority rankings of pollutants of concern in water quality assessments in New Jersey.

Pollutant of Concern	Priority	Reason for Priority
Fecal Coliform in streams	High	Direct human health issues.
Metals, Toxics and Organics	High	Direct human health issue. Important aquatic life issue.
Nitrate	High	Direct human health issue.
Phosphorous, pH, Dissolved Oxygen, temperature, total dissolved solids, total suspended solids, unionized ammonia	Medium	No direct human health issue but may have indirect effect on human health. Important aquatic life issue.
Fecal Coliform in lakes	Low	Either associated with bathing beaches, at which there are extensive controls in place (monitoring/beach closings) or at non-bathing beaches were recreational activities are more controllable than in streams.
Listings for Shellfish	Low	Managed by NSSP classifications.
Macroinvertebrates, Eutrophic Lakes, Aquatic Life	Low	Not directly related to human health issues, but are of environmental importance.

Table 4-2. Key USEPA requirements for establishment of a Total Maximum Daily Load (TMDL).

1	Identification of impaired waterbody, pollutant of concern, pollutant sources and priority ranking
2	Description of applicable water quality standards and numeric water quality target(s)
3	Loading capacity – linking water quality and pollutant sources
4	Load allocations
5	Waste load allocations
6	Margin of safety
7	Seasonal variation
8	Reasonable assurances
9	Monitoring plan to track TMDL effectiveness
10	Implementation (USEPA is not required to and does not approve TMDL implementation plans)
11	Public Participation (stakeholder involvement)

Table 4-3. Estimated cost range to implement total maximum daily load requirements for surface water quality in WMA 6, New Jersey.

	Least Flexible		Moderately Cost-effective		More Cost-effective	
	low	high	low	high	low	high
Point Source*	$1,374,140	$2,766,060	$1,031,240	$2,075,180	$793,750	$1,677,670
Non-point*	$994,410	$2,745,740	$297,180	$2,274,570	$356,870	$2,373,630
Total*	$2,368,550	$5,511,800	$1,328,420	$4,349,750	$1,150,620	$4,051,300

* All estimates in 2010$

Chapter 5 Watershed-based water quality management and socio-economic value

Abstract

This study examines the role of policy and management in assessing water quality and implementing measures to improve water quality through a watershed approach. The dual common threads joining watershed planning and watershed assessment are 1) the Clean Water Act (CWA), and 2) the impact of land use and land cover on water quality. The CWA requires USEPA, who in turn requires each state, to assess, monitor, and plan for improving water quality, with the ultimate goal of all waters of the United States meeting their designated uses through water quality standards. This work investigates outcomes of implementing a land cover based approach to protecting water quality through constraining areas available to be served by sewers. Results indicate that the use of environmentally sensitive areas (ESAs) to define no-build areas for sewers will have a substantial limiting effect on local and regional growth patterns and a simultaneous result of reducing wastewater flow and treatment demand. A first-order, upper bound valuation for the ESAs is performed using reported natural capital figures. This upper bound approach yields values of ecosystem goods and services for lands anticipated to be removed from sewer service areas of $1.6B, $4.5B and $22.3B for New Jersey watershed management areas 1, 6, and 17, respectively.

5.1 Introduction

The need and desire to remove and separate domestic waste from where people live has been a predetermination of civilization for centuries. Viessman, Jr. and Hammer

(1985, Chapter 1) give a detailed accounting of the history of both water supply and the treatment and disposal of domestic wastewater dating back to Sumeria, several thousand years before the common era. Civilization has progressed greatly since swales and glorified ditches dug beside the streets of a city conveyed its wastes “away.” However, modern society still faces significantly degraded natural waters in some areas and slightly degraded waters in many areas, as detailed in previous chapters.

In response to the realization that many waterways in the United States were heavily polluted in the 1960s, the U.S. Congress passed sweeping amendments to the Federal Water Pollution Control Act, in 1972. These amendments, which became known as the Clean Water Act, provided a detailed regulatory procedure for addressing water quality impairments with a goal of zero discharge. The Federal Water Pollution Control Act (33 U.S.C. 1251 et seq.) is primarily known as an effluent-based, point-source control approach to reducing waste entering the nation’s waterways. However, it also has provisions that require attention to nonpoint sources of pollution, as previously discussed in this dissertation, and the law requires states to have a strategy or plan to improve and preserve water quality. Specifically, Sections 201, 208 and 303 of the Federal Water Pollution Control Act (aka, the Clean Water Act) create a framework for water quality planning that includes both point source and distributed sources of waste loading.

Section 201 of the CWA originally required wastewater facilities to identify areas served by sewer systems and future sewer service areas, and to create plans that provide alternatives and environmental impacts of existing and proposed discharges. These plans were required prior to receiving federal loans or grants. While the planning aspects of

Section 201 were eventually phased out and Section 201 became focused on construction grants, the planning requirements were shifted to Section 208 and renamed areawide wastewater treatment plans. Section 208 required states to create new or to designate existing agencies to prepare the areawide wastewater treatment plans. In 1975, EPA, wanting to emphasize the importance of a regional approach for wastewater treatment, created areawide water quality management plans (WQMP) by combining the requirements of Sections 208 and 303 (basin planning) of the Clean Water Act. NJDEP provides additional detail about the history and implementation of water quality management planning at http://www.nj.gov/dep/wqmp/wqmps.html.

In 1977, New Jersey passed the Water Quality Planning Act (N.J.S.A. 58:11A-1 et seq.) and the Water Pollution Control Act (N.J.S.A. 58:10A-1 et seq.) to reinforce the federal laws and provide state specific requirements. These New Jersey laws also required the recently formed New Jersey Department of Environmental Protection (NJDEP) to develop a continuing planning process (CPP) for state-wide water quality management. Since then, additional changes to the federal and state rules implementing these laws have been put in place. One of the more significant changes occurred in 1989, when the New Jersey Water Quality Management Planning rules (N.J.A.C. 7:15) were readopted with a new provision requiring wastewater management plans (WMP) to encourage regional planning for individual treatment facilities. The regional entity responsible is typically a county, a large municipality, or a regional authority. New Jersey also developed 12 areawide water quality management planning areas (WQMPA) to facilitate regional planning for water quality (see Figure 5-1).

In 2000, then New Jersey Governor Whitman issued Executive Order 109 granting the NJDEP the authority to require permitted facilities to conduct alternatives analyses, including detailed land use studies, pollutant loading, and environmental build-out under existing local zoning. In 2008, the WQMP rules were readopted with significant amendments. Several changes were made to codify existing practices established in E.O. 109, such as consistency with existing stormwater management rules for groundwater recharge and to maintain pre-construction water quality. The 2008 amendments also codified the incorporation by reference of riparian zone protections established under the Flood Hazard Area control Act and the requirement for an environmental build-out analysis emphasizing existing and potential future sewer service areas.

The amendments of 2008 also required that municipalities pass an ordinance prohibiting development of slopes over 20% (also known as steep slope ordinance). One of the most controversial aspects of the 2008 amendments, and still controversial today because it has not yet been fully implemented, was a requirement to delineate sewer service area by avoiding environmentally sensitive areas (Johnson 2014, Fallon 2014). The WQMP 2008 rule amendments defined environmentally sensitive areas as contiguous areas of 25 acres (10.1 hectares) or more based on a four-layer data composite. The purpose of this study is to investigate the impact of implementing a landscape-based policy for water quality management, by examining the amount and value of natural capital with and without the policy.

5.2 Methods

The software package ArcGIS 10.0.4 was used to create and modify spatial data and create maps for the research reported here. ArcGIS 10.0.4 is a product of ESRI, Redlands, CA. The GIS data layers used in the analyses presented in this chapter were created as follows:

The state-wide ESA25 layer was converted using *make feature layer* with use ratio policy selected for polygon area. *Use ratio policy* option for feature layers was used for all data where polygon areas were used for data analysis.

Each of the three WMAs was created as individual layers using the *copy feature* tool and selecting each WMA of interest (1, 6, and 17) from the state-wide WMA layer.

A WMA-specific layer with ESA25 data, for each WMA of interest was created using the *clip tool*.

The state-wide sewer service area data layer did not contain a field for "area," so one was created using the *calculate areas* tool and again made into a feature layer with ratio policy set for fields with area information.

Finally, a layer, representing the acreage and location of environmentally sensitive areas to be removed from sewer service areas in WQMPs, was developed using the *intersect* tool.

The ESA mapping results are shown in Figures 5-3, 5-4, and 5-5 for WMA 1, WMA 6 and WMA 17 respectively. Since these mapping exercises, required by the WQMP rules, represent planning or build out scenarios, the results were considered as possible outcomes along an unknown temporal and spatial gradient of land development over time. The resultant land use restriction on new sewer areas were examined using two approaches, 1) change in buildout density with and without the new policy, and 2) utilizing natural capital estimates determined by NJDEP (2007) for the landscape types defined in the WQMP rules.

5.3 Results and Discussion

The most controversial aspect of the newest incarnation of the WQMP rules centers on the requirements to delineate expired sewer service area designations and expired wastewater management plans (WMPs) using a new methodology that incorporates GIS data of four layers of environmentally-sensitive landscapes mapped statewide. It is important to note that New Jersey makes a distinction between 1) a sewer service area, which is a planning attribute that typically contains both sewered and unsewered areas and 2) the parts of cities and towns that already have physical sanitary sewer infrastructure, often referred to as "area served" by sewers.

The four layers are intended to indicate the areas of the state most sensitive to disturbance and high-density development. The four data layers used by New Jersey to delineate sewer service areas are: a) high-value threatened and endangered species habitat (also referred to as landscapes with value 3, 4, or 5 in the State's landscape project database); b) wetlands, c) a 300-foot buffer from the top of bank for all waters with the state's highest water quality classification (C-1); and d) natural heritage priority sites. Natural heritage priority sites are areas of New Jersey in critical need of protection to conserve indigenous biological diversity, particularly "rare plant species and ecological communities" (NJDEP 2007, Natural Heritage Priority Sites GIS data layer – see NJDEP 2014).

Figure 5-2 shows an example of an application of just one of the layers, wetlands, in Monmouth County, New Jersey. In addition to the mapped data mentioned, the new rules would require that Sewer Service Areas avoid including coastal planning areas, floodplains, and floodways. The following sections of this study explore several ways to value this controversial requirement. The Water Quality Management Planning rule amendments of 2008 have yet to be fully implemented, largely because of the disagreement among stakeholders over the perceived value of implementing or not implementing the rules. These divergent perceptions stem primarily from "home rule" in New Jersey. Home rule means that all planning and zoning decisions are made at the local, municipal level, which makes regional zoning and planning difficult and thus rare.

An analysis of the impact of removing environmentally sensitive areas (ESAs), as defined in the 2008 WQMP rules, is presented for three watershed management areas (WMAs). A statewide composite layer representing a union of the four data layers described previously was created, and polygons of 25 acres or larger (ESA25) were retained as required by the WQMP 2008 rules. This chapter continues the use of WMAs 1, 6, and 17 as study areas. Because very few New Jersey municipalities, and none in WMAs 1, 6, or 17, have completed the required environmental build-out analysis, this chapter also incorporates a case study from Howell Township in Monmouth County to examine the impact of the 2008 rules.

The GIS methods applied yield high-resolution spatial information but also important summary data. This summary information can be used by researchers, regulators, legislators, and the public to gauge the impact and potential consequences of regulatory initiatives, such as the recent changes to the WQMP rules discussed in the previous chapter. As described in the last section, the delineation of sewer service areas by local planning authorities, and for the explicit purpose of planning with water quality impacts in mind, must remove any environmentally sensitive areas (ESAs) with 25 or more contiguous acres (10.1 hectares). Table 5-1 provides the results of applying the ESA approach in watershed management areas 1, 6, and 17. This table summarizes the information spatially illustrated in Figures 5-3, 5-4, and 5-5, respectively. The overall amount of land cover defined as environmentally sensitive correlates well with the landscape dominance regime of each watershed management area discussed in Chapter 2.

The Upper Delaware (WMA 1) has a much higher proportion of ESA to total land area, about 72%, compared to WMA 6 and WMA 17, with 43% and 42% respectively. Due to its rural and much greater topographic relief, WMA 1 also has less planned sewer service area (SSA). Table 5-1 indicates that WMA 17 has a large area in planned sewer service area. Although technically accurate, much of the planned SSA in WMA 17 is for small volume community septic systems, 2,000-20,000 gallons per day. These community septic systems would not be expected to yield the same high density development seen in areas served by lateral-based collection systems serving a large central wastewater treatment system. WMA 17 is dominated by coastal plain surface geology, which generally provides fast-draining sandy unconfined aquifers. These sand

and gravel unconfined and unconsolidated surface deposits and shallow aquifers were once considered ideal for community and small discharge commercial septic systems, which is why much of the rural areas of WMA 17 were designated as low-volume sewer service areas. Because much of that same area is also mapped as ESA, there is a large overlap of ESA and sewer service area in WMA 17.

In 2007, the NJDEP published a study of natural capital, the value of goods and services valued by society that derive from natural landscapes and ecosystems. The study was commissioned by the State of New Jersey, and the principle researcher was Robert Costanza (NJDEP 2007). The NJDEP report provides estimates of the “Value of New Jersey’s Natural Capital” in year 2004 dollars (NJDEP 2007, Part 1, Table 5). The report provides these estimates for various “ecosystems” but defines ecosystems based on land use and land cover types. The values are provided on a dollar per unit acre ($/ac) basis as both annual and present value terms. This dissertation finds that three categories of “ecosystem” valued in the NJDEP report provide good proxies for the LULC data layers used to define ESAs: freshwater wetland, forest land, and riparian buffer. The values of natural capital for each of these categories were averaged to obtain a per acre value for ESAs in the WQMP framework. The following values for the natural capital of ESAs were determined to be: $5,672/acre/year with a present value of $189,070/acre in 2004 dollars. Employing the consumer price index (CPI) changes over time provided by the U.S. Department of Labor, the value of the average ESA natural capital in 2010 dollar terms is: $6,547/acre/year and a present value of $218,252/acre.

Table 5-2 presents the total natural capital value of ESA area and the value of areas where ESA and SSA are overlapping for watershed management areas 1, 6, and 17. The values in Table 5-2 should not be interpreted to indicate the value to society if the WQMP rules are fully implemented, but rather as an upper bound. The natural capital values reported should be considered upper bound because the WQMP regulations do not prohibit development in these areas, but by restricting sewers in those areas the development that does occur will be at a lower density. It is anticipated, based on land use conversion trends over the last several decades, Figures 5-6, that all three of these WMAs will continue to experience population growth and an increase in urban land development.

Another approach to valuing the impact of constraints on sewer service area is to analyze the anticipated change in land use and wastewater treatment demands. Wang (2001) finds that land use planning for water quality protection can be used to increase socio-economic benefits to society while balancing protection of critical watershed ecosystems.

Very few municipalities in New Jersey have completed the buildout analysis required under the new WQMP rules. Howell Township in Monmouth County, New Jersey has submitted preliminary information to NJDEP (Dumont 2014). The results of the preliminary buildout analysis for Howell Township are shown in Table 5-3. These estimates indicate that a reduction in built environment, but also in wastewater flows would result from the implementation of the land use component of the new WQMP rules. A reduction of just over four million gallons per day of wastewater is anticipated in Howell Township. This is a significant reduction in the amount of potential pollutant loading to the receiving waters in and around Howell Township, Monmouth County, New Jersey. As mentioned above, regarding natural capital, the full reduction in wastewater flow would not be realized, because lower density non-sewered development is allowed under the new rules.

5.4 Conclusions

The application of GIS-based data and technology, coupled with the natural capital concept of valuing goods and services provided by natural ecosystems gives greater context and a unifying economics-based method of comparison for weighing decisions and assessing impacts of environmental regulation. In particular, this study demonstrates both the need and the ability to translate society's preferences regarding tradeoffs between protection of water quality and the potential for economic growth. The approach outlined in this study as it applies to watershed-based water quality management can lead to more informed decision making and planning. By extending the science-informing-policy rubric to include integrating ecosystem and physical science with social and economic science, watershed management will benefit and more effective solutions for improved water quality will result.

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Figure 5-1. Water Quality Management Planning Areas of New Jersey.

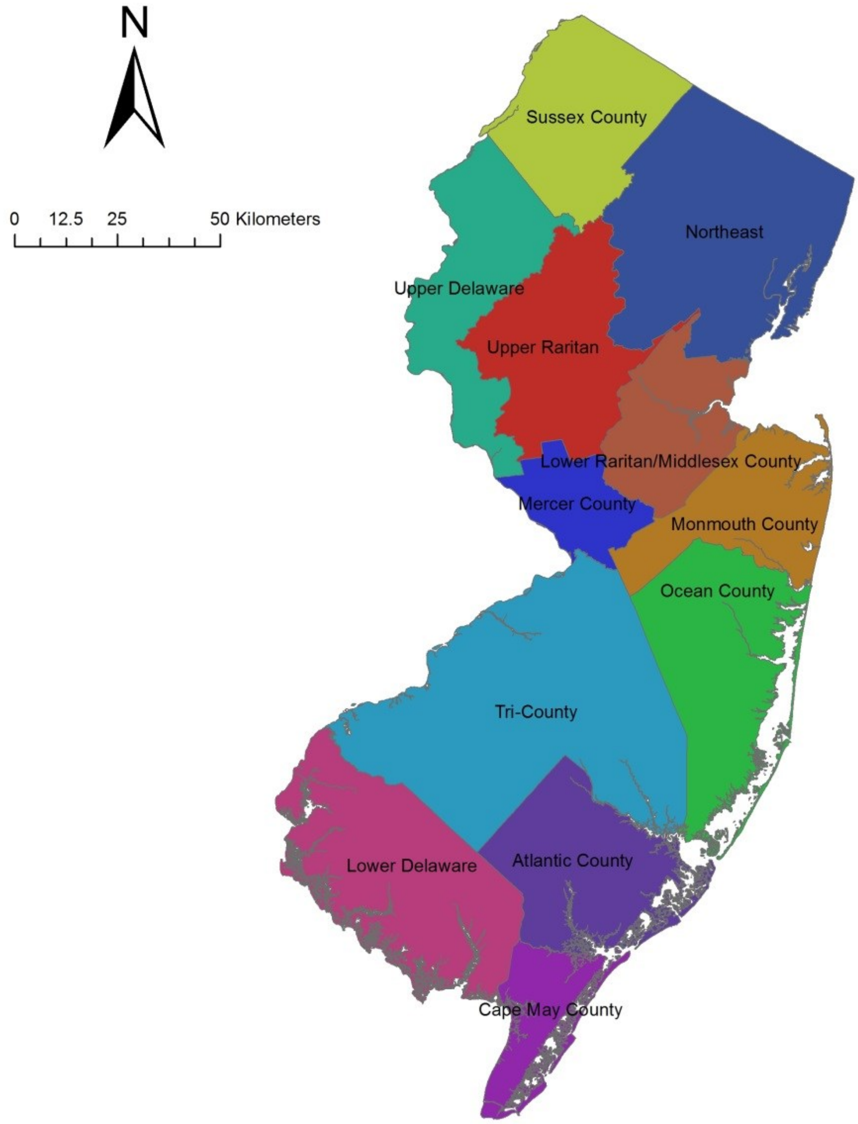


Figure 5-2. Wetlands layer of the Environmentally Sensitive Area (ESA) composite for sewer service area delineation under Water Quality Management Planning rules, from Monmouth County, NJ (not to scale).

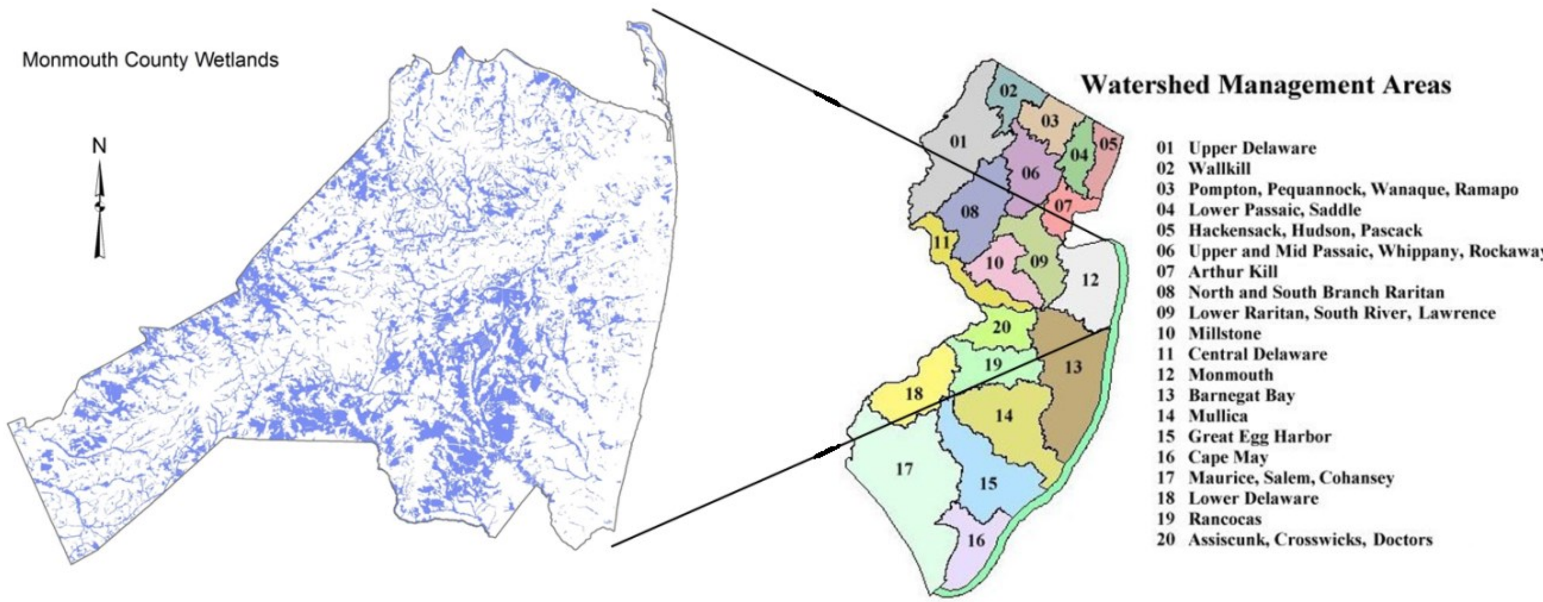


Figure 5-3. WMA 1 environmentally sensitive areas greater than 25 acres with planned sewer service areas (not to scale).

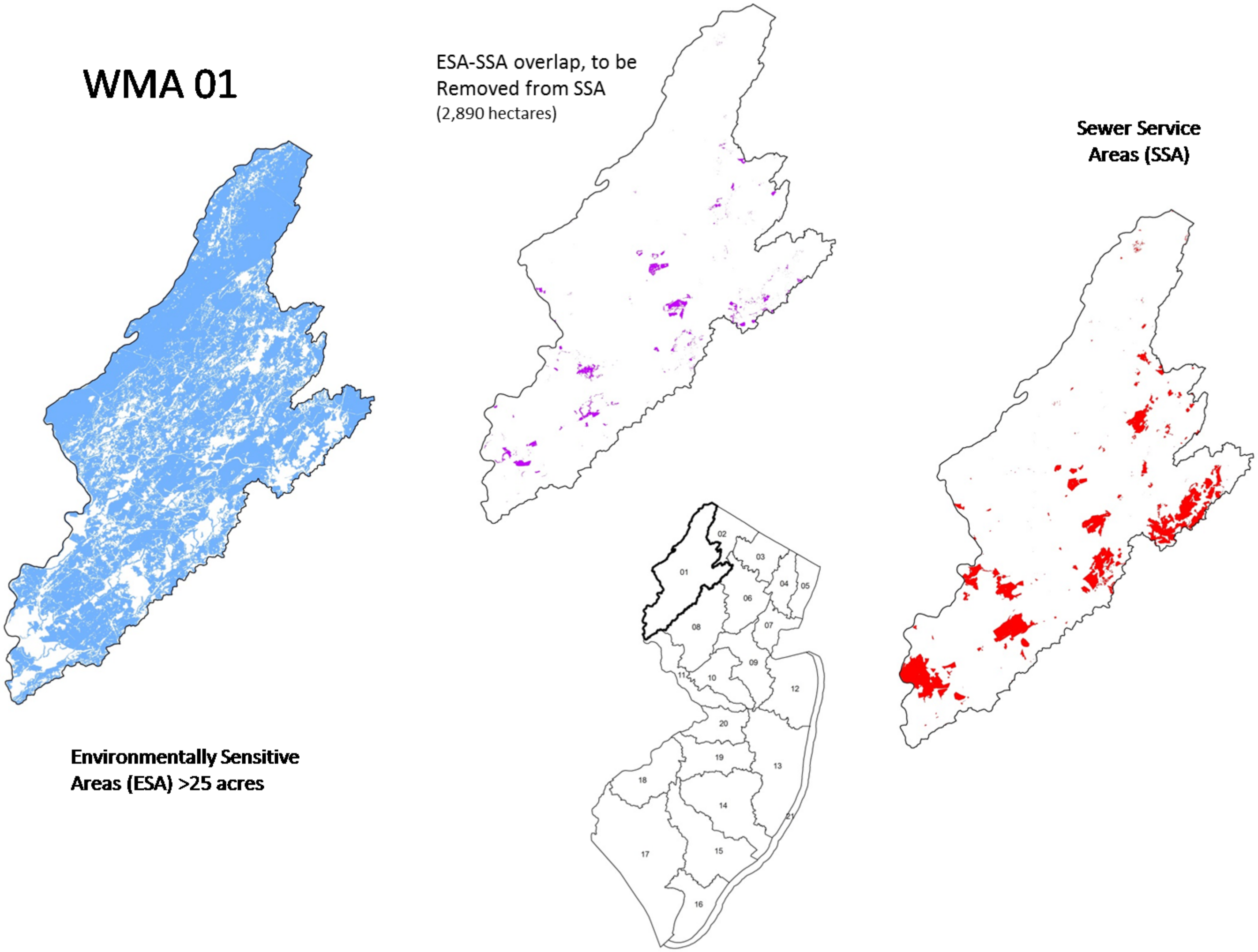


Figure 5-4. WMA 6 environmentally sensitive areas greater than 25 acres with planned sewer service areas (not to scale).

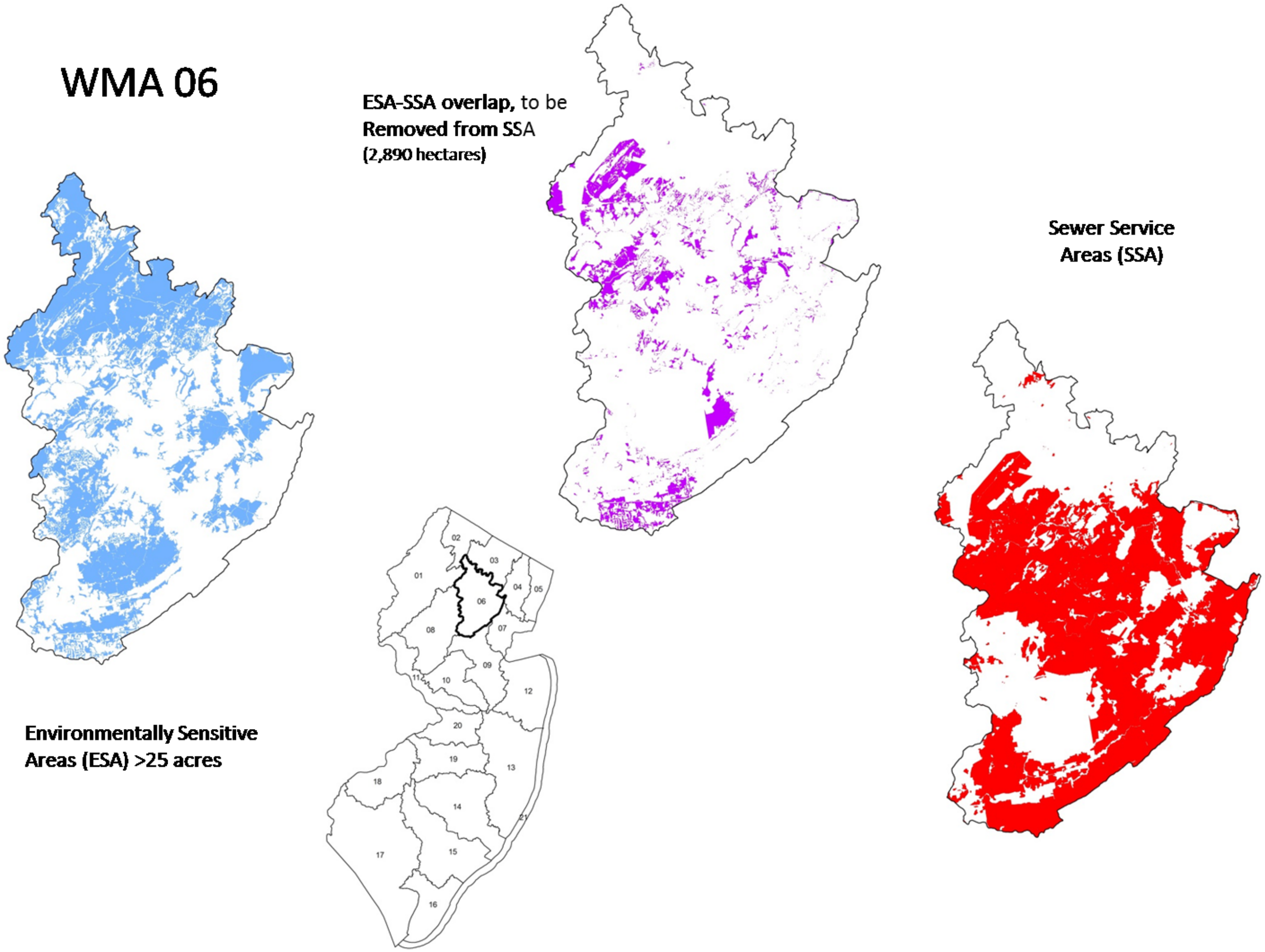


Figure 5-5. WMA 17 environmentally sensitive areas greater than 25 acres with planned sewer service areas (not to scale).

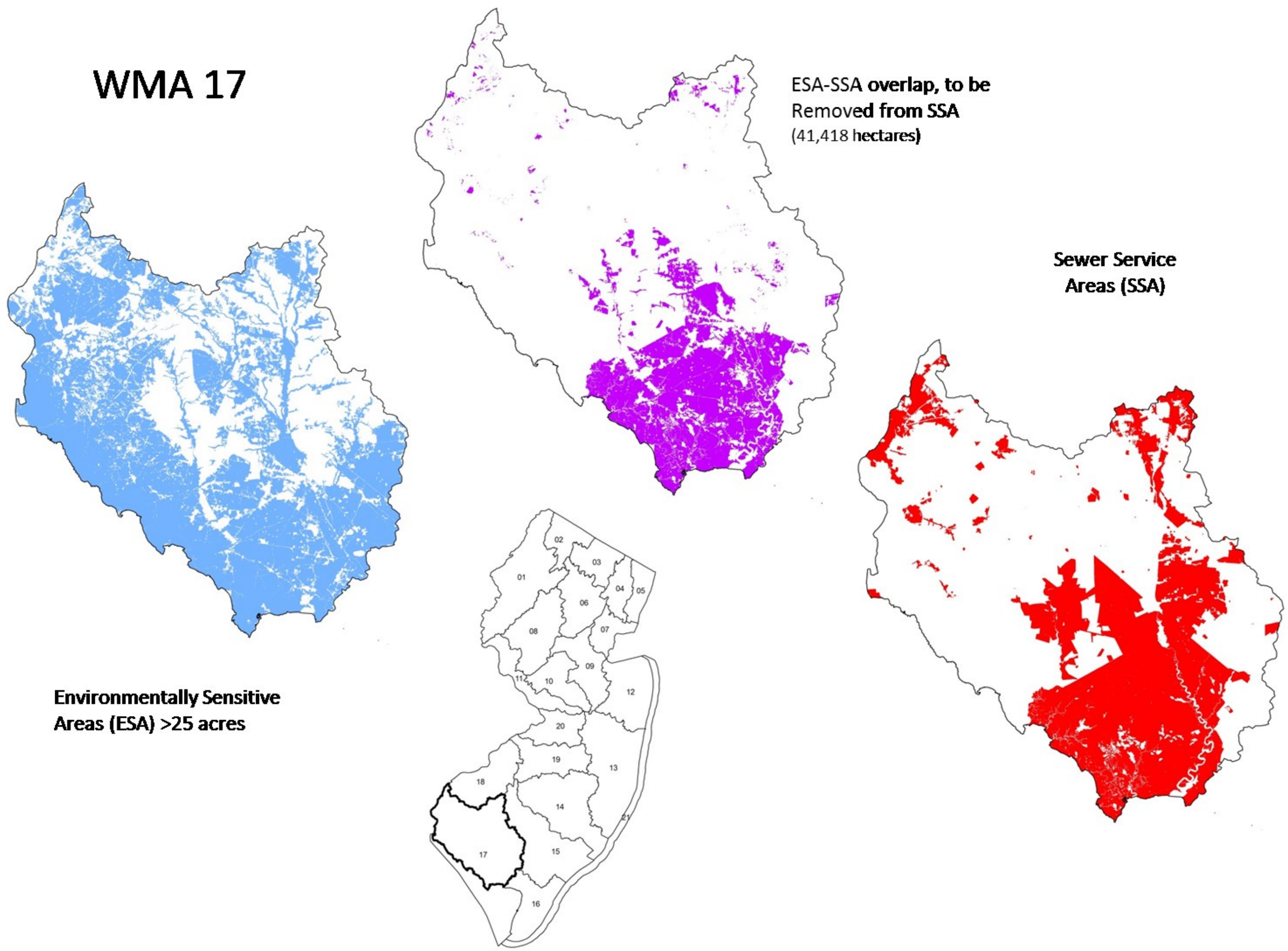


Figure 5-6. Land use and land cover change in WMAs 1, 6, and 17: 1986 – 2007.

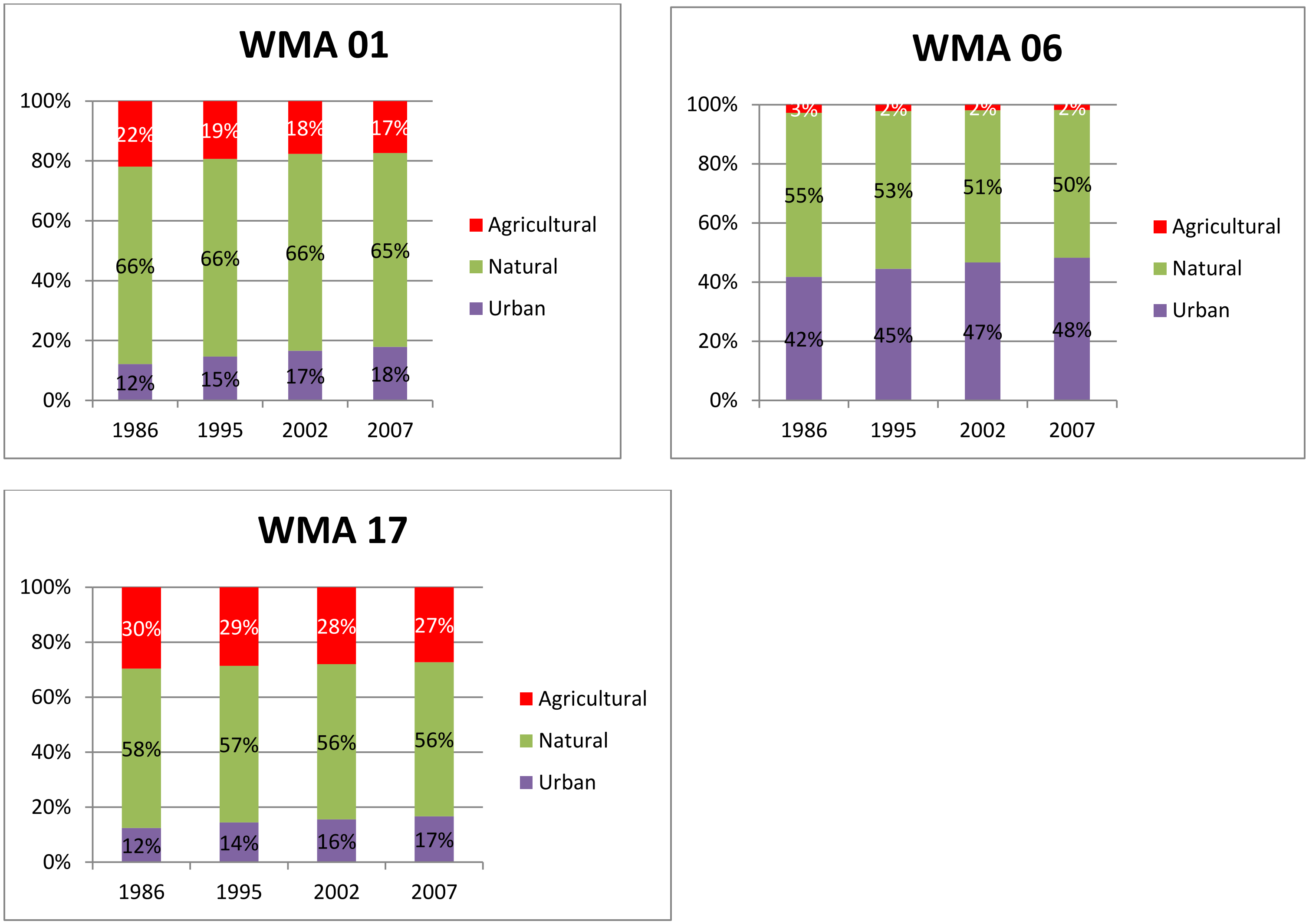


Table 5-1. Overlap of environmentally sensitive areas and sewer service areas in WMAs 1, 6, and 17.

Watershed Management Area		square km	square mi	No. of HUC14 subwatersheds	Water Quality Management Plan Area	ESA>25 (hectares)	Sewer Service Area (SSA) (hectares)	ESA >25 ac overlapping SSA (hectares)	Overlap %
01	Upper Delaware	1,932	746	82	Sussex and Upper Delaware	139,027	14,704	2,890	20%
06	Upper Passaic, Whippany, and Rockaway	936	362	46	Northeast	40,564	50,214	8,416	17%
17	Maurice, Salem, and Cohansey	3,195	1,233	105	Lower Delaware and Tri-County	135,659	78,172	41,418	53%

Table 5-2. Natural capital values for environmentally sensitive areas in WMA 1, 6, and 17.

Watershed Management Area		km^2	Water Quality Management Plan Area	ESA>25 (acres)	Present value of natural capital where ESA>25 ac. (Millions 2010$)	ESA >25 ac overlapping SSA (acres)	Present value of natural capital where ESA>25 ac overlaps SSA (Millions 2010$)
01	Upper Delaware	1,932	Sussex and Upper Delaware	343,277	$74,921	7,141	$1,559
06	Upper Passaic, Whippany, and Rockaway	936	Northeast	100,157	$21,859	20,796	$4,539
17	Maurice, Salem, and Cohansey	3,195	Lower Delaware and Tri-County	334,961	$73,106	102,344	$22,337

Table 5-3. Build-out analysis for Howell Township, Monmouth County, New Jersey.

Development Potential	**# of units**	**Rentable Square Feet (000s, SF)**	**acres**	**Wastewater Flow (MGD)**
Under former WQMP rules				
Residential	9,500		14,106	2.86
Non-residential*		27,700	1,817	2.77
Under new WQMP rules				
Residential	2,820		926	0.85
Non-residential*		7,400	485	0.74

*Non-residential includes: commercial, office, industrial, and warehouse

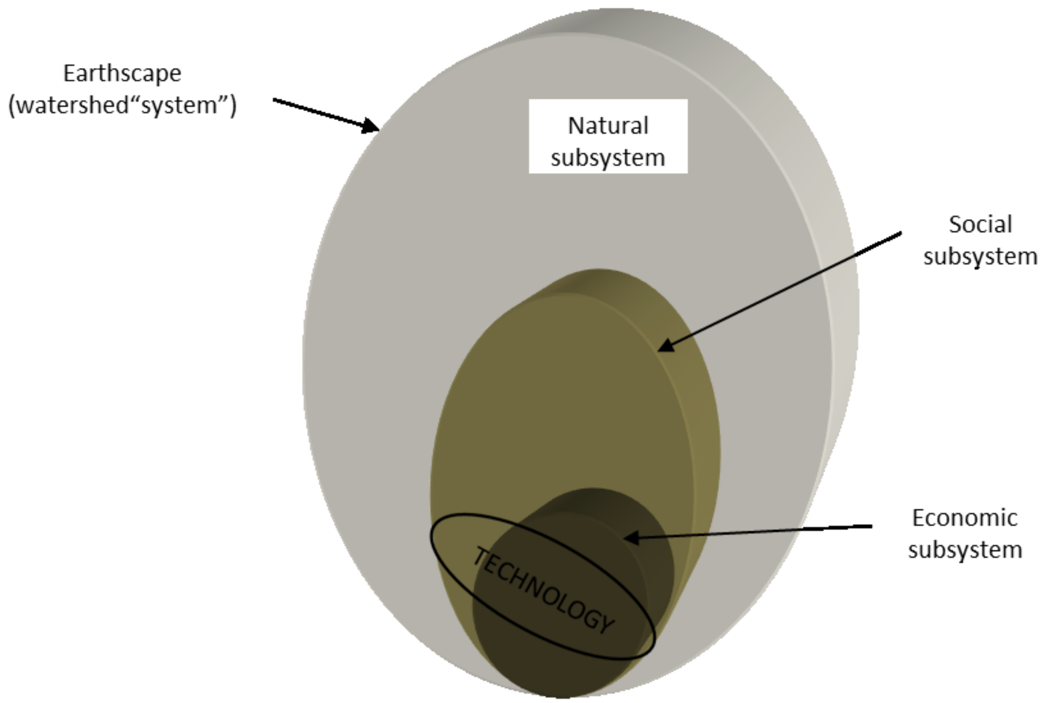
Chapter 6 Dynamic natural-human systems: watershed management as exemplar

6.1 Introduction

The continuing global-scale integration of economies and society coupled with the unsettling exponential population growth (Ehrlich 1969, World Commission on Environment and Development (WCED) 1987) and rapid urban sprawl development in coastal areas (Zhang 2003, Sudhira 2004, Weinstein 2005, Zhu 2007) has forced a worldwide "discussion" of environmental sustainability and particularly sustainable use of natural resources. This research has provided an improved understanding of the dynamic interaction between human and nature that impact sustainability of urbanizing watersheds. By constructing a conceptual model of the dynamic system (Figure 6-1), it is clear that the system or overall Earthscape (in this research a watershed is considered as "the system") consists of interdependent subsystems.

This conceptual model shows that both the technology and economic subsystems are nested within the social or human subsystem which is nested within the larger natural or ecologic subsystem. Together these subsystems and their inherent interrelationships and hierarchical nature comprise the Earthscape, or in this case the watershed, and point to the importance for environmental policy to be informed by science and skilled managers. Other similar models that acknowledge the interconnectedness of ecological, anthropic, and hydrological subsystems include Naveh's total human ecosystem (THE) approach (Naveh 2005), ecological footprints (Wackernagel and Rees 1996), the World3 model (Meadows et al. 2004), and the adaptive cycles with resilience metaphor of Holling and Gunderson (2002) and Levin (2006).

Figure 6-1. Conceptual model of the dynamic watershed "system." (adapted from Naveh 2005)



The diagram in Figure 6-1 shows that both the technology and economic subsystems are nested within the social or human subsystem which is nested within the larger natural or ecologic subsystem. Together these subsystems and their inherent interrelationships and hierarchical nature comprise the Earthscape, or in this case the watershed.

6.2 Sustainability and watershed management

The modern sustainability discussion began in earnest with the United Nations (UN) Conference on the Human Environment held in Stockholm, Sweden in 1972. A direct result of this conference was the creation of the United Nations Environment Program (UNEP), whose mission is "To provide leadership and encourage partnership in caring for the environment by inspiring, informing, and enabling nations and peoples to improve their quality of life without compromising that of future generations." UNEP has a clear focus on sustainability. Over the next two decades, researchers, policy-makers, and the public continued to absorb and create greater knowledge of the issues affecting global sustainability. By 1992, the year of the UN Conference on Environment and Development or the Earth Summit, it was clear sustainability was an issue that could only be addressed through approaches that include environmental, economic, and social aspects of natural resource use and waste generation.

Since 1987 when the Bruntland Commission (WCED 1987) presented their report on sustainable development to the UN, many scientists, researchers, and governments have been wrestling with the complex issues of how to change many entrenched bureaucratic, socio-economic, and cultural systems that impede movement toward a more sustainable state (Mihelcic et al. 2003, Smith and Zhang 2004, Marshall and Toffel 2005, and Wackernagel and Rees 1996). Long before 1987, some researchers were concerned about ecological and water resource systems sustainability. In a seminal work on global change, Meadows et al. (1972 and updated in Meadows 2004) used system dynamic modeling to estimate changes in global resource and population stocks as a measure of global sustainability. These works are still regarded as major achievements in the use of systems thinking and systems dynamic modeling of environmental systems at the global scale.

The detailed philosophical and intellectual foundation regarding sustainability of complex ecological and environmental systems has been discussed by Forrester (1971), Hardin (1968), and Ehrlich (1969) to push, pull and pester human civilization toward a sustainable existence within the greater Earthscape. In the meantime, many individuals and organizations (e.g., United States Geological Survey [USGS] 1998, United States Environmental Protection Agency [USEPA] 1997 and 2000, The Heinz Center 2002 and 2003, Gleick 2003, Kranz 2004) have begun to research and identify various indicators of ecosystem health and sustainability. The Sustainable Water Resources Roundtable (SWRR), a part of the Advisory Committee on Water Information (ACWI), has created a list of almost 400 potential water sustainability criteria and indicators (SWRR 2005). The ACWI advises the many federal agencies responsible for managing various aspects of the nation’s water resources.

The current research focuses on analyzing land cover and land use change affecting sustainability of water resources in a watershed context. To fit with current definitions and understanding of sustainability, this research incorporates economic, social, and environmental relationships within the context of water resource management and systems thinking. Lant (2004) suggests that “sustainability is inevitably based in systems thinking” and that “ecological economics helps us make more sustainable water resources decisions.” The results from this study recommend to use a systems approach to investigate management for watershed sustainability by including feedback relationships between social, economic, and natural capital.

In the United States, great strides were made to improve water quality in the 1970s during the early years of the Clean Water Act and other similar environmental protection laws and regulations. However, the last 25 years have seen only modest improvements and in some areas a backslide to lower water quality, mostly as a result of nonpoint source pollution stemming from changes in land use and land cover and/or wastewater treatment facilities expanding to their permitted limits. Based on data from the United States Environmental Protection Agency (USEPA), the National Research Council has estimated that in the United States alone there are more than “21,000 river segments, lakes and estuaries” that have been identified as violating one or more water quality standards (NRC 2001). The New Jersey Department of Environmental Protection (NJDEP) estimates that 76% of the assessed nontidal river miles in New Jersey did not meet surface water quality standards for at least one parameter (NJDEP 2004). In addition, water supply demand continually increases, creating tension and conflict between competing interests including water quality and quantity requirements for ecological needs.

Many new approaches are being written into agency rules and regulations and even laws. Some of these have recently begun to be implemented. Weinstein (2009) notes the importance of “placing humans in the landscape within the broader context of the biological and physical environment.”

There are four major contributing factors impeding sustainability in water resources in the United States: 1) significant contributions of nonpoint source pollution, 2) rapidly changing land use (from urban decay and agricultural to suburban and exurban sprawl in western countries and rapid urban growth and deforestation in many developing areas of the world), 3) global climate change, and 4) threats to existing high quality waters. The GAO (2004a and 2004b) recognized these critical issues and the data gaps needed to help inform policy and decision makers when they wrote, "The availability of timely, reliable, and complete data about the nation's waters has significant environmental and financial implications."

6.3 Systems thinking for watershed management

Water protection strategies and related data collection efforts are typically conceived and implemented with a myopic focus on a single indicator, such as dissolved oxygen, or PCBs, or for a uniquely individual project, such as clean-up of a contaminated site. The Government Accounting Office (GAO 2004a p.8) noted that, "Organizations often collect data to achieve very specific missions, which sometimes makes officials unwilling or unable to modify their data collection approaches to make the results more widely usable." Additionally, these policies often have a single-discipline focus (e.g., ecological health or economic growth) and are rarely evaluated for their impact at a holistic system level on a regional scale. Instead, they are often reviewed only for the impact on a single indicator at the point of discharge or on a limited reach of stream or for an individual lake for example. Indeed, the NRC (1999, p272) observed that, "Fragmented consideration of ecological, economic, and social concerns in water resource management has not served the nation well…." This narrow view may result in unseen and therefore unpredicted effects and does little to inform about broader watershed sustainability. Gleick (2003) suggests that a new "soft path" for water management is necessary, which includes the goal of "sustainable system operation over time" for water supply and management.

An analysis using a system dynamics approach focuses on process and feedback relationships among system components from all sectors influencing watershed sustainability. A systems approach utilizing key indicators is better suited to capture various integrated outcomes of a management decision than traditional single-issue analysis of policy decisions (Smith and Zhang 2004, Kranz et al. 2004). Watersheds provide natural, physical boundaries leading to a management approach that more fully supports discussion and analysis of sustainability in a metadisciplinary manner integrating ecological, economic, and social goals and objectives (see Mihelcic et al. 2003 for a discussion of sustainability science as a metadiscipline). Naveh (2005) uses the term "transdisciplinary" to refer to a systems approach for ecological restoration, which is based on system dynamics modeling and critical for guiding sustainability science and policy.

6.4 Summary and recommendation

Watershed management or a watershed approach has evolved over the past decade as the preferred strategy for addressing the large and complex task of managing water resources. Conceptually, watershed-based approach integrates the many social, economic, and ecological facets of the water resources management paradigm. The National Research Council (1999) stated that “The watershed approach acknowledges linkages between uplands and downstream areas, and between surface and groundwater, and reduces chances that attempts to solve problems in one realm will cause problems in others.” Smith and Zhang (2004) wrote “the nation needs a framework for tracking and understanding changes to the health of its waterbodies that takes into account environmental, economical, and cultural interrelationships.” These statements indicate clearly that many researchers recognize the complex, dynamic nature of watersheds and the cause-effect feedback mechanisms prevalent in watershed management.

Many current water resource problems, from water quality (Beck 2005a) to flooding (Ahmad 2004) to socio-economic use of water (Guo 2001) involve many stakeholders and actors in addition to overlying complex scientific questions with high degrees of uncertainty and variability. Several of these include reservoir flow management for water supply (Ganji 2006) and ecological needs (Eheart 2004, Baron et al. 2002), as well as problems of water supply and infrastructure under dynamic changes in demographic and land use patterns (Kenel 2005). Recent articles (Vorosmarty et al. 2004, Braimoh and Craswell 2006, and Jain et al. 2006) have highlighted the need to consider global water systems research a priority and to incorporate new data and influences, such as climate change and rapid transformation of the landscape. Bella (1997) discusses watershed management in the context of dynamic modeling of organizational systems and observes that organizational systems in technologically developed societies are complex, nonlinear, and adaptive (after NRC 1999).

The concept of watershed sustainability as a function of pollutant loading, ecological integrity, land use, land value, water supply and demand, water value, and public policy can be evaluated within a system dynamics framework. Three subsystems that can be used to represent the watershed system and some examples of indicators linked to each are:

Hydrologic: stream flow, water availability, pollutant loading, water quality, assimilative capacity;

Ecologic: ecological integrity (e.g., index of biological integrity (IBI)), land cover, pollutant loading;

Anthropic (Socio-economic): population, land use, water demand, return flows (point source and nonpoint sources), level of treatment, cost to treat water supply, cost to treat return flows, total daily loading, land value

Systems thinking promote a "big picture" view. It is a perspective that encourages investigation of structure and relationships between components rather than the components themselves. It is a methodology for evaluating processes and patterns of change rather than measuring individual outcomes or discrete results. Applying systems thinking to watersheds and sustainability science can provide a way for a larger part of society to participate in the decisions that impact water quality.

Water resources policy and some aspects of watershed management have been studied and modeled using system dynamic models. Simonovic and Fahmy (1999) and Simonovic et al. (1997) used an object-oriented systems model to analyze water resource policy options at the national strategic level for Egypt. Similarly, Xu et al. (2002) used system dynamics to analyze sustainability of water resources (supply and demand) in the Yellow River basin in China. Elshorbagy and Ormsbee (2006) used STELLA, a system dynamics (SD) software platform, to model surface water quality management for fecal coliform in southeastern Kentucky. Ahmad and Simonovic (2004) used a SD model linked to a GIS to simulate alternative flood management strategies for Manitoba, Canada, and Elshorbagy et al. (2007) used system dynamics to simulate hydrological processes in reconstructed watersheds.

Future research can extend the previous work of others in three important ways by: 1) implementing watershed policy analysis at the regional watershed scale. Previous studies have tended toward national-level analysis (e.g., Smith and Zhang 2005, Simonovic and Fahmy 1999, Xu et al. 2002, and Simonovic et al. 1997); 2) integrating anthropic behavior into systems modeling for watershed sustainability analysis; and further integrating the role of GIS and watershed sustainability into the systems modeling approach.

The concept proposed here for further investigation can better illustrate watershed sustainability in urbanizing watersheds as a dynamic system that includes important feedback mechanisms between and within natural subsystems (hydrologic and ecologic) and human subsystems (social and economic). In addition, the system dynamic approach may illuminate important system behavior that cannot be recognized by static models and models that do not account for feedback between system components and thus more fully inform management decisions.

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Appendix A Benthic Macroinvertebrate Sampling Results

Table A-1. New Jersey Macroinvertebrate Round 3, sampling scores by Site ID.

SITE	WMA	Macro Index	SCORE	Quality	Regulatory Status	Percent Urban	Percent Ag Land
AN0297	2	HGMI	30.96	Fair	Not Attaining	36.2	1.1
AN0301	2	HGMI	30.43	Fair	Not Attaining	12.9	26.6
AN0300	2	HGMI	47.21	Good	Attaining	24.4	8.2
AN0299	2	HGMI	40.09	Fair	Not Attaining	24.4	8.2
AN0298	2	HGMI	54.08	Good	Attaining	26.4	1.2
AN0303	2	HGMI	67.92	Excellent	Attaining	11.7	25.3
AN0304	2	HGMI	33.67	Fair	Not Attaining	14.4	31.4
AN0305	2	HGMI	53.76	Good	Attaining	14.2	26.3
AN0306	2	HGMI	65.52	Excellent	Attaining	17.9	23.7
AN0308	2	HGMI	9.63	Poor	Not Attaining	12.8	21.6
AN0309	2	HGMI	31.53	Fair	Not Attaining	12.8	21.6
AN0309A	2	HGMI	85.26	Excellent	Attaining	12.8	21.6
AN0307	2	HGMI	32.92	Fair	Not Attaining	14.7	25.2
AN0302	2	HGMI	23.29	Fair	Not Attaining	19.5	16.9
AN0296	2	HGMI	36.85	Fair	Not Attaining	25.4	6.7
AN0294	2	HGMI	49.94	Good	Attaining	14.8	3.1
AN0295	2	HGMI	43.17	Good	Attaining	14.8	3.1
AN0213	6	HGMI	27.15	Fair	Not Attaining	40.3	7.9
AN0214	6	HGMI	73.80	Excellent	Attaining	40.3	7.9
AN0216	6	HGMI	50.59	Good	Attaining	29.9	6.7
AN0215	6	HGMI	75.78	Excellent	Attaining	29.9	6.7
AN0218	6	HGMI	17.17	Poor	Not Attaining	49.1	12.8
AN0217	6	HGMI	59.03	Good	Attaining	49.1	12.8
AN0220	6	HGMI	12.62	Poor	Not Attaining	51.8	6.2
AN0221	6	HGMI	23.53	Fair	Not Attaining	51.8	6.2
AN0219	6	HGMI	8.61	Poor	Not Attaining	39.2	9.3
AN0222	6	HGMI	14.87	Poor	Not Attaining	26.5	2.7
AN0223	6	HGMI	6.62	Poor	Not Attaining	26.5	2.7
AN0227	6	HGMI	15.92	Poor	Not Attaining	38.1	6.6
AN0224	6	HGMI	32.70	Fair	Not Attaining	38.1	6.6
AN0226	6	HGMI	31.10	Fair	Not Attaining	44.6	7.5
AN0225	6	HGMI	30.78	Fair	Not Attaining	44.6	7.5
AN0227A	6	HGMI	26.94	Fair	Not Attaining	73.8	1.5
AN0228	6	HGMI	32.86	Fair	Not Attaining	41.6	5.7
AN0230	6	HGMI	28.48	Fair	Not Attaining	47.0	4.7

SITE	WMA	Macro Index	SCORE	Quality	Regulatory Status	Percent Urban	Percent Ag Land
AN0229	6	HGMI	21.34	Fair	Not Attaining	47.0	4.7
AN0231E	6	HGMI	41.05	Fair	Not Attaining	65.9	0.2
AN0231D	6	HGMI	26.54	Fair	Not Attaining	65.9	0.2
AN0231A	6	HGMI	18.60	Poor	Not Attaining	50.3	4.0
AN0231	6	HGMI	17.07	Poor	Not Attaining	51.4	3.6
AN0231C	6	HGMI	25.66	Fair	Not Attaining	51.8	0.4
AN0232	6	HGMI	67.82	Excellent	Attaining	38.0	1.4
AN0233	6	HGMI	46.43	Good	Attaining	33.9	2.4
AN0234A	6	HGMI	33.57	Fair	Not Attaining	55.8	2.5
AN0234	6	HGMI	30.92	Fair	Not Attaining	52.8	1.9
AN0235	6	HGMI	30.16	Fair	Not Attaining	52.8	1.9
AN0238B	6	HGMI	31.98	Fair	Not Attaining	69.5	0.1
AN0236	6	HGMI	15.78	Poor	Not Attaining	71.6	0.1
AN0237	6	HGMI	27.48	Fair	Not Attaining	57.6	0.2
AN0238	6	HGMI	14.51	Poor	Not Attaining	58.6	0.9
AN0239	6	HGMI	60.35	Good	Attaining	21.5	0.7
AN0241	6	HGMI	20.77	Poor	Not Attaining	20.9	0.5
AN0240	6	HGMI	30.89	Fair	Not Attaining	20.9	0.5
AN0242	6	HGMI	33.00	Fair	Not Attaining	23.5	0.2
AN0244	6	HGMI	50.52	Good	Attaining	50.8	0.9
AN0243	6	HGMI	33.42	Fair	Not Attaining	34.1	0.4
AN0246	6	HGMI	27.32	Fair	Not Attaining	22.2	0.2
AN0245	6	HGMI	85.07	Excellent	Attaining	22.2	0.2
AN0247	6	HGMI	45.96	Good	Attaining	55.3	1.5
AN0249	6	HGMI	20.45	Poor	Not Attaining	22.9	2.3
AN0248	6	HGMI	28.75	Fair	Not Attaining	34.2	0.6
AN0250	6	HGMI	42.81	Good	Attaining	33.7	0.8
AN0254	6	HGMI	36.35	Fair	Not Attaining	45.5	0.6
AN0253	6	HGMI	30.07	Fair	Not Attaining	45.5	0.6
AN0252	6	HGMI	70.95	Excellent	Attaining	45.5	0.6
AN0251	6	HGMI	31.27	Fair	Not Attaining	44.1	0.9
AN0274A	6	HGMI	22.54	Fair	Not Attaining	47.0	1.9
AN0258	3	HGMI	38.56	Fair	Not Attaining	3.6	0.1
AN0259	3	HGMI	77.81	Excellent	Attaining	3.6	0.1
AN0260	3	HGMI	61.52	Good	Attaining	1.9	0.2
AN0262	3	HGMI	35.11	Fair	Not Attaining	6.6	0.5
AN0261	3	HGMI	31.53	Fair	Not Attaining	6.6	0.5
AN0264	3	HGMI	51.84	Good	Attaining	7.9	0.5

SITE	WMA	Macro Index	SCORE	Quality	Regulatory Status	Percent Urban	Percent Ag Land
AN0263	3	HGMI	24.15	Fair	Not Attaining	7.9	0.5
AN0265	3	HGMI	52.50	Good	Attaining	38.7	0.1
AN0255C	3	HGMI	18.62	Poor	Not Attaining	22.5	1.0
AN0255D	3	HGMI	75.74	Excellent	Attaining	22.5	1.0
AN0255	3	HGMI	34.93	Fair	Not Attaining	17.4	0.6
AN0256A	3	HGMI	28.21	Fair	Not Attaining	38.0	0.1
AN0257	3	HGMI	30.53	Fair	Not Attaining	19.7	0.4
AN0256	3	HGMI	24.06	Fair	Not Attaining	19.7	0.4
AN0266	3	HGMI	41.44	Fair	Not Attaining	47.8	0.7
AN0267	3	HGMI	38.37	Fair	Not Attaining	43.3	0.6
AN0269	3	HGMI	9.18	Poor	Not Attaining	46.8	2.8
AN0268	3	HGMI	16.32	Poor	Not Attaining	27.6	0.6
AN0270	3	HGMI	14.30	Poor	Not Attaining	27.6	0.6
AN0275A	4	HGMI	22.40	Fair	Not Attaining	74.4	0.1
AN0275	4	HGMI	19.72	Poor	Not Attaining	75.1	0.1
AN0272	4	HGMI	30.65	Fair	Not Attaining	65.8	0.1
AN0273	4	HGMI	21.18	Fair	Not Attaining	65.8	0.1
AN0276	4	HGMI	23.01	Fair	Not Attaining	70.8	0.3
AN0277A	4	HGMI	35.25	Fair	Not Attaining	87.2	0.2
AN0277	4	HGMI	24.54	Fair	Not Attaining	87.2	0.2
AN0271	4	HGMI	12.22	Poor	Not Attaining	79.4	0.0
AN0278	4	HGMI	12.99	Poor	Not Attaining	43.3	1.3
AN0274	4	HGMI	29.31	Fair	Not Attaining	42.8	1.3
AN0283	4	HGMI	29.08	Fair	Not Attaining	67.7	1.7
AN0285	4	HGMI	44.62	Good	Attaining	75.9	1.0
AN0286	4	HGMI	37.49	Fair	Not Attaining	75.9	1.0
AN0284	4	HGMI	29.66	Fair	Not Attaining	75.9	1.0
AN0287	4	HGMI	22.37	Fair	Not Attaining	75.9	1.0
AN0288	4	HGMI	21.44	Fair	Not Attaining	80.0	0.8
AN0279	4	HGMI	44.08	Good	Attaining	74.9	1.3
AN0281	4	HGMI	43.35	Good	Attaining	74.9	1.3
AN0280	4	HGMI	41.13	Fair	Not Attaining	74.9	1.3
AN0289	4	HGMI	24.50	Fair	Not Attaining	78.9	0.9
AN0290	4	HGMI	15.56	Poor	Not Attaining	81.2	0.7
AN0291	4	HGMI	24.74	Fair	Not Attaining	82.6	0.6
AN0282	4	HGMI	30.22	Fair	Not Attaining	75.4	1.2
AN0292	4	HGMI	13.05	Poor	Not Attaining	91.8	0.0
AN0292A	4	HGMI	11.15	Poor	Not Attaining	91.8	0.0

SITE	WMA	Macro Index	SCORE	Quality	Regulatory Status	Percent Urban	Percent Ag Land
AN0206	5	HGMI	13.75	Poor	Not Attaining	82.1	1.0
AN0207	5	HGMI	31.27	Fair	Not Attaining	82.1	1.0
AN0205	5	HGMI	23.84	Fair	Not Attaining	76.7	0.1
AN0209	5	HGMI	13.29	Poor	Not Attaining	84.6	0.0
AN0208	5	HGMI	63.85	Excellent	Attaining	57.6	0.2
AN0210	5	HGMI	29.90	Fair	Not Attaining	77.2	0.5
AN0211	5	HGMI	18.92	Poor	Not Attaining	92.6	0.0
AN0212	5	HGMI	22.57	Fair	Not Attaining	87.3	0.2
AN0204	7	HGMI	20.86	Poor	Not Attaining	94.2	0.0
AN0192	7	HGMI	18.25	Poor	Not Attaining	59.2	0.1
AN0194	7	HGMI	12.57	Poor	Not Attaining	79.2	0.1
AN0193	7	HGMI	24.19	Fair	Not Attaining	79.2	0.1
AN0195	7	HGMI	24.90	Fair	Not Attaining	81.9	0.2
AN0196	7	HGMI	14.71	Poor	Not Attaining	75.6	0.6
AN0197	7	HGMI	20.78	Poor	Not Attaining	81.9	0.5
AN0199	7	HGMI	14.62	Poor	Not Attaining	81.9	0.5
AN0198	7	HGMI	10.26	Poor	Not Attaining	81.9	0.5
AN0200	7	HGMI	17.72	Poor	Not Attaining	88.0	0.0
AN0201	7	HGMI	25.23	Fair	Not Attaining	88.0	0.0
AN0456	12	CPMI	14.00	Good	Attaining	54.9	3.5
AN0458	12	CPMI	2.00	Poor	Not Attaining	63.9	1.8
AN0457	12	CPMI	0.00	Poor	Not Attaining	63.9	1.8
AN0459	12	CPMI	2.00	Poor	Not Attaining	74.5	0.2
AN0460	12	CPMI	4.00	Poor	Not Attaining	68.7	3.0
AN0461	12	CPMI	6.00	Fair	Not Attaining	67.8	0.6
AN0466	12	CPMI	8.00	Fair	Not Attaining	45.8	17.1
AN0465	12	CPMI	6.00	Fair	Not Attaining	45.8	17.1
AN0467	12	CPMI	6.00	Fair	Not Attaining	43.0	17.7
AN0468	12	CPMI	6.00	Fair	Not Attaining	43.0	17.7
AN0470	12	CPMI	10.00	Fair	Not Attaining	50.2	15.7
AN0469	12	CPMI	6.00	Fair	Not Attaining	50.2	15.7
AN0471	12	CPMI	6.00	Fair	Not Attaining	54.5	16.5
AN0473	12	CPMI	4.00	Poor	Not Attaining	27.5	5.6
AN0472	12	CPMI	4.00	Poor	Not Attaining	44.9	13.5
AN0476	12	CPMI	12.00	Good	Attaining	28.3	6.7
AN0475	12	CPMI	6.00	Fair	Not Attaining	28.3	6.7
AN0464	12	CPMI	6.00	Fair	Not Attaining	62.3	3.4
AN0462	12	CPMI	4.00	Poor	Not Attaining	48.2	11.9

SITE	WMA	Macro Index	SCORE	Quality	Regulatory Status	Percent Urban	Percent Ag Land
AN0477	12	CPMI	8.00	Fair	Not Attaining	70.8	1.4
AN0481	12	CPMI	8.00	Fair	Not Attaining	32.8	2.2
AN0479	12	CPMI	8.00	Fair	Not Attaining	67.0	0.3
AN0480	12	CPMI	6.00	Fair	Not Attaining	67.0	0.3
AN0482	12	CPMI	14.00	Good	Attaining	55.3	1.2
AN0483	12	CPMI	10.00	Fair	Not Attaining	66.1	8.3
AN0484	12	CPMI	8.00	Fair	Not Attaining	66.1	8.3
AN0485	12	CPMI	2.00	Poor	Not Attaining	33.9	11.7
AN0487	12	CPMI	8.00	Fair	Not Attaining	50.5	13.4
AN0486	12	CPMI	8.00	Fair	Not Attaining	50.5	13.4
AN0488	12	CPMI	8.00	Fair	Not Attaining	50.5	13.4
AN0489	12	CPMI	16.00	Good	Attaining	43.6	15.1
AN0491	12	CPMI	4.00	Poor	Not Attaining	23.6	4.9
AN0492	12	CPMI	8.00	Fair	Not Attaining	23.6	4.9
AN0493	12	CPMI	10.00	Fair	Not Attaining	40.8	13.1
AN0490	12	CPMI	8.00	Fair	Not Attaining	40.8	13.1
AN0494	12	CPMI	10.00	Fair	Not Attaining	25.1	5.2
AN0495	12	CPMI	26.00	Excellent	Attaining	22.2	5.1
AN0496	12	CPMI	18.00	Good	Attaining	34.3	10.7
AN0497	12	CPMI	28.00	Excellent	Attaining	34.3	10.7
AN0311	8	HGMI	51.23	Good	Attaining	42.1	2.1
AN0312	8	HGMI	44.32	Good	Attaining	43.9	5.4
AN0310	8	HGMI	23.01	Fair	Not Attaining	33.8	8.9
AN0315	8	HGMI	49.19	Good	Attaining	36.7	8.8
AN0314	8	HGMI	36.70	Fair	Not Attaining	36.7	8.8
AN0313	8	HGMI	76.19	Excellent	Attaining	36.7	8.8
AN0316	8	HGMI	52.42	Good	Attaining	31.7	13.0
AN0317	8	HGMI	68.82	Excellent	Attaining	31.7	13.0
AN0318	8	HGMI	73.04	Excellent	Attaining	21.6	20.3
AN0319	8	HGMI	67.02	Excellent	Attaining	21.2	19.5
AN0321	8	HGMI	53.74	Good	Attaining	24.7	17.2
AN0320	8	HGMI	73.04	Excellent	Attaining	22.8	17.5
AN0324	8	HGMI	37.04	Fair	Not Attaining	34.3	29.3
AN0323	8	HGMI	73.54	Excellent	Attaining	34.3	29.3
AN0325B	8	HGMI	69.00	Excellent	Attaining	20.8	49.2
AN0325	8	HGMI	67.91	Excellent	Attaining	20.8	49.2
AN0322	8	HGMI	50.19	Good	Attaining	29.0	19.4
AN0324A	8	HGMI	75.95	Excellent	Attaining	29.0	19.4

SITE	WMA	Macro Index	SCORE	Quality	Regulatory Status	Percent Urban	Percent Ag Land
AN0326	8	HGMI	64.80	Excellent	Attaining	29.2	19.7
AN0327	8	HGMI	61.50	Good	Attaining	22.7	17.2
AN0329	8	HGMI	37.69	Fair	Not Attaining	30.8	19.9
AN0328	8	HGMI	63.30	Excellent	Attaining	30.8	19.9
AN0330	8	HGMI	25.07	Fair	Not Attaining	42.7	14.9
AN0331	8	HGMI	51.04	Good	Attaining	34.3	19.9
AN0332	8	HGMI	63.38	Excellent	Attaining	20.3	52.2
AN0335	8	HGMI	48.77	Good	Attaining	21.8	47.7
AN0334	8	HGMI	34.06	Fair	Not Attaining	21.8	47.7
AN0333	8	HGMI	36.52	Fair	Not Attaining	33.1	36.6
AN0337	8	HGMI	46.12	Good	Attaining	26.3	39.6
AN0336	8	HGMI	63.65	Excellent	Attaining	26.3	39.6
AN0338	8	HGMI	54.86	Good	Attaining	29.6	25.6
AN0339	8	HGMI	52.90	Good	Attaining	37.7	30.1
AN0340	8	HGMI	50.32	Good	Attaining	37.7	30.1
AN0343	8	HGMI	28.78	Fair	Not Attaining	45.2	21.2
AN0342	8	HGMI	68.00	Excellent	Attaining	45.2	21.2
AN0341	8	HGMI	38.14	Fair	Not Attaining	30.9	25.7
AN0356	8	HGMI	8.95	Poor	Not Attaining	42.0	2.6
AN0357	8	HGMI	52.51	Good	Attaining	39.4	5.5
AN0358	8	HGMI	36.39	Fair	Not Attaining	34.1	9.9
AN0359	8	HGMI	64.98	Excellent	Attaining	34.1	9.9
AN0361	8	HGMI	66.54	Excellent	Attaining	12.0	20.7
AN0362	8	HGMI	60.89	Good	Attaining	15.1	47.3
AN0370	8	HGMI	62.58	Good	Attaining	26.9	21.4
AN0363	8	HGMI	80.06	Excellent	Attaining	26.9	21.4
AN0364	8	HGMI	82.17	Excellent	Attaining	25.2	24.1
AN0365	8	HGMI	81.45	Excellent	Attaining	25.2	24.1
AN0369	8	HGMI	35.16	Fair	Not Attaining	29.6	21.7
AN0366	8	HGMI	80.62	Excellent	Attaining	29.6	21.7
AN0367	8	HGMI	44.90	Good	Attaining	37.0	18.0
AN0368	8	HGMI	23.79	Fair	Not Attaining	37.0	18.0
AN0360	8	HGMI	85.32	Excellent	Attaining	32.5	12.0
AN0344	8	HGMI	53.30	Good	Attaining	44.0	4.2
AN0345	8	HGMI	90.88	Excellent	Attaining	44.0	4.2
AN0344A	8	HGMI	65.13	Excellent	Attaining	44.0	4.2
AN0347	8	HGMI	84.83	Excellent	Attaining	42.2	4.6
AN0346	8	HGMI	50.86	Good	Attaining	39.6	7.1

SITE	WMA	Macro Index	SCORE	Quality	Regulatory Status	Percent Urban	Percent Ag Land
AN0348	8	HGMI	84.42	Excellent	Attaining	39.6	7.1
AN0349	8	HGMI	78.82	Excellent	Attaining	38.5	11.8
AN0350	8	HGMI	59.72	Good	Attaining	36.8	15.6
AN0352	8	HGMI	18.91	Poor	Not Attaining	36.6	11.6
AN0351	8	HGMI	55.85	Good	Attaining	36.6	11.6
AN0353	8	HGMI	46.15	Good	Attaining	36.6	11.6
AN0355	8	HGMI	51.68	Good	Attaining	15.2	47.8
AN0354	8	HGMI	31.58	Fair	Not Attaining	15.2	47.8
AN0371	8	HGMI	20.79	Poor	Not Attaining	30.3	19.8
AN0372	8	HGMI	49.08	Good	Attaining	50.3	16.4
AN0373	8	HGMI	28.48	Fair	Not Attaining	50.3	16.4
AN0374	8	HGMI	54.54	Good	Attaining	32.4	19.2
AN0376	9	HGMI	21.62	Fair	Not Attaining	75.8	0.3
AN0375	9	HGMI	18.22	Poor	Not Attaining	32.9	22.5
AN0377	9	HGMI	28.30	Fair	Not Attaining	32.9	22.5
AN0390	10	HGMI	46.32	Good	Attaining	14.4	24.0
AN0391	10	HGMI	51.97	Good	Attaining	17.7	25.5
AN0392	10	HGMI	45.70	Good	Attaining	24.6	25.0
AN0393	10	HGMI	41.56	Fair	Not Attaining	29.2	21.6
AN0394	10	HGMI	15.83	Poor	Not Attaining	46.7	16.4
AN0379	10	CPMI	6.00	Fair	Not Attaining	27.0	31.8
AN0378	10	CPMI	22.00	Excellent	Attaining	27.0	31.8
AN0380	10	CPMI	12.00	Good	Attaining	24.7	24.1
AN0381	10	CPMI	8.00	Fair	Not Attaining	34.5	24.0
AN0382	10	CPMI	6.00	Fair	Not Attaining	29.1	27.7
AN0382B	10	CPMI	6.00	Fair	Not Attaining	29.1	27.7
AN0385	10	CPMI	4.00	Poor	Not Attaining	32.0	23.9
AN0386	10	CPMI	10.00	Fair	Not Attaining	44.0	25.1
AN0388	10	CPMI	6.00	Fair	Not Attaining	31.3	14.7
AN0387	10	CPMI	8.00	Fair	Not Attaining	38.5	16.5
AN0384	10	CPMI	10.00	Fair	Not Attaining	60.2	13.0
AN0383	10	CPMI	8.00	Fair	Not Attaining	60.2	13.0
AN0395	10	HGMI	19.39	Poor	Not Attaining	38.2	20.7
AN0396	10	HGMI	28.19	Fair	Not Attaining	38.2	20.7
AN0397	10	HGMI	18.86	Poor	Not Attaining	38.2	20.2
AN0398	10	HGMI	30.76	Fair	Not Attaining	21.0	27.0
AN0401	10	HGMI	48.62	Good	Attaining	32.3	19.5
AN0405	10	HGMI	41.88	Fair	Not Attaining	32.3	19.5

SITE	WMA	Macro Index	SCORE	Quality	Regulatory Status	Percent Urban	Percent Ag Land
AN0399	10	HGMI	48.92	Good	Attaining	14.3	3.2
AN0400	10	HGMI	44.48	Good	Attaining	21.2	14.6
AN0402	10	HGMI	39.15	Fair	Not Attaining	29.2	21.1
AN0403	10	HGMI	45.26	Good	Attaining	21.7	12.5
AN0404	10	HGMI	36.63	Fair	Not Attaining	37.8	18.6
AN0407	10	HGMI	45.09	Good	Attaining	37.3	20.0
AN0406	10	HGMI	24.29	Fair	Not Attaining	37.3	20.0
AN0408	10	HGMI	14.18	Poor	Not Attaining	53.3	14.7
AN0409	10	HGMI	29.70	Fair	Not Attaining	37.8	20.3
AN0410	10	HGMI	24.83	Fair	Not Attaining	37.8	20.3
AN0411	10	HGMI	25.99	Fair	Not Attaining	52.0	16.4
AN0412	10	HGMI	18.46	Poor	Not Attaining	57.6	10.8
AN0413	10	HGMI	16.41	Poor	Not Attaining	57.6	10.8
AN0414	10	HGMI	35.25	Fair	Not Attaining	39.1	19.7
AN0421	9	HGMI	26.40	Fair	Not Attaining	51.8	0.7
AN0422	9	HGMI	27.47	Fair	Not Attaining	67.1	0.3
AN0423	9	HGMI	30.39	Fair	Not Attaining	64.4	0.4
AN0419	9	HGMI	35.37	Fair	Not Attaining	55.3	2.5
AN0418	9	HGMI	22.73	Fair	Not Attaining	55.3	2.5
AN0417	9	HGMI	33.86	Fair	Not Attaining	47.0	5.5
AN0416	9	HGMI	32.35	Fair	Not Attaining	47.0	5.5
AN0415	9	HGMI	31.84	Fair	Not Attaining	68.0	0.0
AN0424B	9	HGMI	9.15	Poor	Not Attaining	75.0	0.2
AN0424	9	HGMI	16.55	Poor	Not Attaining	82.3	0.4
AN0425	9	HGMI	18.34	Poor	Not Attaining	77.9	1.7
AN0425A	9	HGMI	23.66	Fair	Not Attaining	77.9	1.7
AN0426	9	HGMI	14.58	Poor	Not Attaining	74.4	0.7
AN0428	9	HGMI	31.54	Fair	Not Attaining	38.8	19.4
AN0427	9	HGMI	23.46	Fair	Not Attaining	38.8	19.4
AN0429	9	HGMI	8.72	Poor	Not Attaining	91.4	0.3
AN0420	9	HGMI	38.95	Fair	Not Attaining	52.5	3.4
AN0430	9	HGMI	12.03	Poor	Not Attaining	42.6	4.3
AN0432	9	HGMI	43.60	Good	Attaining	54.2	0.9
AN0433	9	HGMI	38.88	Fair	Not Attaining	55.4	15.1
AN0431	9	HGMI	29.27	Fair	Not Attaining	46.7	10.7
AN0434	9	HGMI	26.64	Fair	Not Attaining	50.6	9.5
AN0435	9	HGMI	16.52	Poor	Not Attaining	55.7	8.7
AN0438	9	CPMI	16.00	Good	Attaining	41.5	19.1

SITE	WMA	Macro Index	SCORE	Quality	Regulatory Status	Percent Urban	Percent Ag Land
AN0437	9	CPMI	14.00	Good	Attaining	41.5	19.1
AN0439	9	CPMI	20.00	Good	Attaining	31.2	17.0
AN0440	9	CPMI	6.00	Fair	Not Attaining	38.5	13.8
AN0443	9	CPMI	8.00	Fair	Not Attaining	43.3	18.6
AN0441	9	CPMI	6.00	Fair	Not Attaining	43.3	18.6
AN0442	9	CPMI	6.00	Fair	Not Attaining	43.3	18.6
AN0445	9	CPMI	10.00	Fair	Not Attaining	61.5	8.9
AN0444	9	CPMI	10.00	Fair	Not Attaining	61.5	8.9
AN0447	9	CPMI	4.00	Poor	Not Attaining	66.4	6.2
AN0446	9	CPMI	8.00	Fair	Not Attaining	66.4	6.2
AN0449	9	CPMI	2.00	Poor	Not Attaining	60.4	8.7
AN0448	9	CPMI	10.00	Fair	Not Attaining	60.4	8.7
AN0450	9	CPMI	4.00	Poor	Not Attaining	35.6	2.1
AN0451	9	CPMI	8.00	Fair	Not Attaining	50.7	7.9
AN0453	9	CPMI	4.00	Poor	Not Attaining	39.0	3.7
AN0452	9	CPMI	4.00	Poor	Not Attaining	44.4	10.1
AN0436	9	HGMI	27.64	Fair	Not Attaining	88.2	0.0
AN0001	1	HGMI	28.50	Fair	Not Attaining	6.3	4.1
AN0002	1	HGMI	64.88	Excellent	Attaining	6.3	4.1
AN0003	1	HGMI	67.84	Excellent	Attaining	14.1	5.3
AN0005	1	HGMI	52.74	Good	Attaining	7.5	2.1
AN0004	1	HGMI	91.37	Excellent	Attaining	7.5	2.1
AN0005A	1	HGMI	54.19	Good	Attaining	9.3	12.0
AN0006	1	HGMI	70.53	Excellent	Attaining	2.1	0.4
AN0007	1	HGMI	37.50	Fair	Not Attaining	3.7	4.0
AN0008	1	HGMI	73.84	Excellent	Attaining	3.7	4.0
AN0009	1	HGMI	54.42	Good	Attaining	1.3	1.6
AN0010	1	HGMI	91.43	Excellent	Attaining	1.3	1.6
AN0011	1	HGMI	78.30	Excellent	Attaining	1.3	1.6
AN0012	1	HGMI	80.30	Excellent	Attaining	1.5	2.4
AN0023	1	HGMI	28.18	Fair	Not Attaining	13.2	5.3
AN0023A	1	HGMI	70.63	Excellent	Attaining	13.2	5.3
AN0024	1	HGMI	83.31	Excellent	Attaining	11.5	5.9
AN0017	1	HGMI	13.49	Poor	Not Attaining	18.0	3.9
AN0018	1	HGMI	11.69	Poor	Not Attaining	18.0	3.9
AN0020	1	HGMI	56.38	Good	Attaining	18.2	9.3
AN0019	1	HGMI	28.67	Fair	Not Attaining	18.2	9.3
AN0016	1	HGMI	20.98	Poor	Not Attaining	15.3	24.9

SITE	WMA	Macro Index	SCORE	Quality	Regulatory Status	Percent Urban	Percent Ag Land
AN0014	1	HGMI	30.50	Fair	Not Attaining	27.5	16.6
AN0015	1	HGMI	28.26	Fair	Not Attaining	28.0	16.9
AN0021	1	HGMI	58.38	Good	Attaining	21.7	16.9
AN0022	1	HGMI	24.62	Fair	Not Attaining	19.3	15.1
AN0026	1	HGMI	47.42	Good	Attaining	17.5	15.5
AN0025	1	HGMI	29.50	Fair	Not Attaining	17.5	15.5
AN0028	1	HGMI	61.55	Good	Attaining	13.6	10.7
AN0029	1	HGMI	74.94	Excellent	Attaining	13.6	10.7
AN0030	1	HGMI	23.83	Fair	Not Attaining	12.2	5.3
AN0031	1	HGMI	79.49	Excellent	Attaining	12.2	5.3
AN0032	1	HGMI	54.93	Good	Attaining	17.4	15.5
AN0027	1	HGMI	52.29	Good	Attaining	17.4	15.5
AN0032A	1	HGMI	63.65	Excellent	Attaining	17.4	15.5
AN0013	1	HGMI	68.83	Excellent	Attaining	10.8	2.9
AN0033	1	HGMI	48.70	Good	Attaining	14.3	31.3
AN0034	1	HGMI	72.81	Excellent	Attaining	14.3	31.3
AN0035	1	HGMI	17.23	Poor	Not Attaining	15.1	19.7
AN0036	1	HGMI	18.26	Poor	Not Attaining	18.8	17.7
AN0037	1	HGMI	61.07	Good	Attaining	18.8	17.7
AN0038	1	HGMI	25.42	Fair	Not Attaining	11.4	15.0
AN0039	1	HGMI	53.36	Good	Attaining	15.7	18.6
AN0040A	1	HGMI	11.77	Poor	Not Attaining	15.0	29.3
AN0040	1	HGMI	32.98	Fair	Not Attaining	11.4	24.5
AN0041	1	HGMI	19.95	Poor	Not Attaining	15.1	17.4
AN0044	1	HGMI	25.78	Fair	Not Attaining	16.1	6.7
AN0042	1	HGMI	20.13	Poor	Not Attaining	17.2	8.9
AN0048	1	HGMI	56.63	Good	Attaining	15.0	19.8
AN0043	1	HGMI	52.92	Good	Attaining	15.0	19.8
AN0046	1	HGMI	31.13	Fair	Not Attaining	13.8	31.7
AN0045	1	HGMI	40.30	Fair	Not Attaining	15.9	26.6
AN0047	1	HGMI	65.53	Excellent	Attaining	11.7	29.6
AN0049	1	HGMI	46.94	Good	Attaining	23.8	38.1
AN0050	1	HGMI	49.00	Good	Attaining	14.5	40.6
AN0052	1	HGMI	31.68	Fair	Not Attaining	24.4	28.3
AN0051	1	HGMI	72.86	Excellent	Attaining	24.4	28.3
AN0053	1	HGMI	24.51	Fair	Not Attaining	40.2	32.3
AN0054	1	HGMI	84.70	Excellent	Attaining	10.9	17.2
AN0055	1	HGMI	65.39	Excellent	Attaining	10.9	17.2

SITE	WMA	Macro Index	SCORE	Quality	Regulatory Status	Percent Urban	Percent Ag Land
AN0056	1	HGMI	65.39	Excellent	Attaining	22.4	16.1
AN0057	1	HGMI	57.09	Good	Attaining	20.0	23.5
AN0058	1	HGMI	31.53	Fair	Not Attaining	20.0	23.5
AN0060	1	HGMI	51.49	Good	Attaining	15.5	28.1
AN0059	1	HGMI	65.78	Excellent	Attaining	15.5	28.1
AN0061	1	HGMI	71.07	Excellent	Attaining	19.3	32.1
AN0063	1	HGMI	49.26	Good	Attaining	36.2	0.0
AN0062	1	HGMI	28.66	Fair	Not Attaining	36.2	0.0
AN0065	1	HGMI	43.34	Good	Attaining	24.9	1.6
AN0064	1	HGMI	45.51	Good	Attaining	18.6	0.9
AN0066	1	HGMI	43.39	Good	Attaining	18.6	0.9
AN0067	1	HGMI	31.51	Fair	Not Attaining	36.8	14.6
AN0068	1	HGMI	33.37	Fair	Not Attaining	28.2	1.6
AN0069	1	HGMI	44.10	Good	Attaining	28.5	4.3
AN0070	1	HGMI	26.12	Fair	Not Attaining	28.5	4.3
AN0071	1	HGMI	40.76	Fair	Not Attaining	26.7	8.3
AN0072	1	HGMI	36.10	Fair	Not Attaining	27.0	10.3
AN0073	1	HGMI	58.85	Good	Attaining	25.2	16.1
AN0074	1	HGMI	51.52	Good	Attaining	24.7	16.8
AN0076	11	HGMI	79.71	Excellent	Attaining	23.3	26.8
AN0075	11	HGMI	74.82	Excellent	Attaining	23.3	26.8
AN0077	11	HGMI	74.38	Excellent	Attaining	23.3	26.8
AN0078	11	HGMI	60.63	Good	Attaining	20.9	40.7
AN0079	11	HGMI	54.33	Good	Attaining	20.9	40.7
AN0080	11	HGMI	66.01	Excellent	Attaining	18.0	49.8
AN0083	11	HGMI	56.48	Good	Attaining	17.0	49.2
AN0082	11	HGMI	73.59	Excellent	Attaining	17.0	49.2
AN0081	11	HGMI	66.05	Excellent	Attaining	17.0	49.2
AN0084	11	HGMI	68.01	Excellent	Attaining	10.9	39.1
AN0085	11	HGMI	63.29	Excellent	Attaining	10.2	22.4
AN0086	11	HGMI	55.51	Good	Attaining	12.4	54.3
AN0087	11	HGMI	61.53	Good	Attaining	13.1	43.4
AN0088	11	HGMI	51.25	Good	Attaining	13.1	43.4
AN0089	11	HGMI	56.51	Good	Attaining	12.7	40.5
AN0090	11	HGMI	46.57	Good	Attaining	11.3	33.2
AN0091	11	HGMI	45.49	Good	Attaining	11.3	33.2
AN0093	11	HGMI	59.78	Good	Attaining	14.0	26.4
AN0092	11	HGMI	40.83	Fair	Not Attaining	14.0	26.4

SITE	WMA	Macro Index	SCORE	Quality	Regulatory Status	Percent Urban	Percent Ag Land
AN0094	11	HGMI	57.13	Good	Attaining	11.9	37.1
AN0095	11	HGMI	46.68	Good	Attaining	11.9	37.1
AN0096	11	HGMI	54.79	Good	Attaining	14.3	31.1
AN0097	11	HGMI	55.97	Good	Attaining	16.4	35.9
AN0098	11	HGMI	41.60	Fair	Not Attaining	16.4	35.9
AN0099	11	HGMI	32.56	Fair	Not Attaining	26.0	17.2
AN0100	11	HGMI	59.73	Good	Attaining	13.4	34.3
AN0101	11	HGMI	27.47	Fair	Not Attaining	13.4	34.3
AN0102	11	HGMI	62.42	Good	Attaining	27.1	38.6
AN0105	11	HGMI	56.03	Good	Attaining	27.1	38.6
AN0106	11	HGMI	44.81	Good	Attaining	36.4	31.3
AN0103	11	HGMI	38.12	Fair	Not Attaining	36.4	31.3
AN0104	11	HGMI	21.47	Fair	Not Attaining	36.4	31.3
AN0107	11	HGMI	19.19	Poor	Not Attaining	70.0	9.9
AN0108	11	CPMI	4.00	Poor	Not Attaining	17.4	22.2
AN0109B	11	CPMI	6.00	Fair	Not Attaining	15.3	50.2
AN0109A	11	CPMI	2.00	Poor	Not Attaining	15.8	36.5
AN0109	11	CPMI	8.00	Fair	Not Attaining	27.8	27.4
AN0110	11	HGMI	18.84	Poor	Not Attaining	39.3	20.0
AN0111	11	HGMI	27.61	Fair	Not Attaining	39.3	20.0
AN0114	11	HGMI	11.08	Poor	Not Attaining	78.8	3.0
AN0113	11	HGMI	27.04	Fair	Not Attaining	78.8	3.0
AN0115	11	CPMI	4.00	Poor	Not Attaining	57.5	13.1
AN0115A	11	CPMI	6.00	Fair	Not Attaining	57.5	13.1
AN0117	11	CPMI	2.00	Poor	Not Attaining	77.8	2.6
AN0112	11	HGMI	15.68	Poor	Not Attaining	73.0	3.9
AN0116	11	HGMI	22.06	Fair	Not Attaining	50.2	16.5
AN0119A	20	PMI	48.44	Fair	Not Attaining	51.2	0.2
AN0119	20	PMI	41.36	Fair	Not Attaining	24.5	9.4
AN0120	20	PMI	42.18	Fair	Not Attaining	25.3	17.3
AN0122	20	PMI	29.94	Poor	Not Attaining	17.7	9.7
AN0123	20	CPMI	8.00	Fair	Not Attaining	17.7	9.7
AN0124	20	CPMI	22.00	Excellent	Attaining	17.2	23.4
AN0121	20	PMI	33.72	Poor	Not Attaining	25.0	20.1
AN0125B	20	CPMI	8.00	Fair	Not Attaining	22.1	23.7
AN0126B	20	CPMI	4.00	Poor	Not Attaining	21.4	26.5
AN0125	20	CPMI	12.00	Good	Attaining	21.4	26.5
AN0126A	20	CPMI	8.00	Fair	Not Attaining	10.3	56.4

SITE	WMA	Macro Index	SCORE	Quality	Regulatory Status	Percent Urban	Percent Ag Land
AN0127	20	CPMI	6.00	Fair	Not Attaining	21.6	40.3
AN0128	20	CPMI	4.00	Poor	Not Attaining	14.9	47.8
AN0129	20	CPMI	10.00	Fair	Not Attaining	20.8	43.9
AN0131A	20	CPMI	4.00	Poor	Not Attaining	38.5	15.1
AN0132	20	CPMI	10.00	Fair	Not Attaining	14.2	52.2
AN0133	20	CPMI	8.00	Fair	Not Attaining	14.2	52.2
AN0136	20	CPMI	4.00	Poor	Not Attaining	19.3	39.1
AN0135	20	CPMI	10.00	Fair	Not Attaining	19.3	39.1
AN0137	20	CPMI	10.00	Fair	Not Attaining	22.4	41.9
AN0139	20	CPMI	12.00	Good	Attaining	12.3	36.2
AN0138	20	PMI	35.31	Fair	Not Attaining	12.3	36.2
AN0140	20	PMI	31.58	Poor	Not Attaining	11.9	36.1
AN0141O	20	CPMI	2.00	Poor	Not Attaining	11.9	36.1
AN0141	20	CPMI	8.00	Fair	Not Attaining	18.9	34.9
AN0142C	20	CPMI	12.00	Good	Attaining	23.2	31.9
AN0149A	19	PMI	59.02	Good	Attaining	36.6	0.3
AN0149B	19	PMI	36.97	Fair	Not Attaining	36.6	0.3
AN0143	19	PMI	55.78	Fair	Not Attaining	21.7	0.6
AN0146	19	PMI	60.52	Good	Attaining	0.5	0.1
AN0147	19	PMI	66.29	Excellent	Attaining	4.7	0.1
AN0144	19	PMI	59.59	Good	Attaining	6.3	0.9
AN0148	19	PMI	51.23	Fair	Not Attaining	6.3	0.9
AN0145	19	PMI	67.32	Excellent	Attaining	6.3	0.9
AN0149	19	PMI	53.35	Fair	Not Attaining	11.5	3.1
AN0150	19	PMI	33.82	Poor	Not Attaining	17.2	24.7
AN0151A	19	PMI	59.82	Good	Attaining	11.9	4.5
AN0151	19	PMI	55.64	Fair	Not Attaining	14.5	6.7
AN0153	19	PMI	61.14	Good	Attaining	2.6	4.6
AN0152	19	PMI	56.36	Good	Attaining	18.7	12.3
AN0154	19	PMI	62.93	Good	Attaining	12.1	5.8
AN0155	19	PMI	58.54	Good	Attaining	12.1	5.8
AN0157	19	PMI	27.84	Poor	Not Attaining	5.2	39.1
AN0157A	19	PMI	58.95	Good	Attaining	5.2	39.1
AN0156	19	PMI	58.43	Good	Attaining	12.2	8.7
AN0167	19	PMI	38.36	Fair	Not Attaining	27.3	1.7
AN0168	19	PMI	37.32	Fair	Not Attaining	41.7	1.0
AN0163	19	PMI	25.06	Poor	Not Attaining	58.1	1.9
AN0166	19	PMI	30.10	Poor	Not Attaining	39.2	3.6

SITE	WMA	Macro Index	SCORE	Quality	Regulatory Status	Percent Urban	Percent Ag Land
AN0165	19	PMI	57.79	Good	Attaining	39.2	3.6
AN0164	19	PMI	75.70	Excellent	Attaining	39.2	3.6
AN0159	19	PMI	49.01	Fair	Not Attaining	27.2	6.8
AN0158	19	PMI	41.65	Fair	Not Attaining	21.1	0.9
AN0162	19	PMI	27.50	Poor	Not Attaining	43.5	2.3
AN0160	19	PMI	46.62	Fair	Not Attaining	22.6	10.8
AN0170	19	PMI	33.61	Poor	Not Attaining	36.4	7.2
AN0169	19	PMI	52.53	Fair	Not Attaining	36.4	7.2
AN0171A	19	PMI	22.33	Poor	Not Attaining	18.4	38.1
AN0172	19	PMI	32.84	Poor	Not Attaining	26.3	13.3
AN0173	19	CPMI	6.00	Fair	Not Attaining	26.3	13.3
AN0175	19	CPMI	6.00	Fair	Not Attaining	61.1	15.1
AN0176	18	CPMI	6.00	Fair	Not Attaining	69.0	11.1
AN0177	18	CPMI	6.00	Fair	Not Attaining	78.8	3.5
AN0178	18	PMI	43.80	Fair	Not Attaining	72.4	2.6
AN0179	18	CPMI	8.00	Fair	Not Attaining	72.4	2.6
AN0182	18	CPMI	4.00	Poor	Not Attaining	80.3	0.6
AN0183	18	CPMI	6.00	Fair	Not Attaining	84.2	0.4
AN0186	18	PMI	38.34	Fair	Not Attaining	68.8	3.7
AN0188	18	CPMI	8.00	Fair	Not Attaining	73.7	2.5
AN0187	18	CPMI	6.00	Fair	Not Attaining	73.7	2.5
AN0189	18	CPMI	12.00	Good	Attaining	64.3	0.7
AN0190	18	CPMI	2.00	Poor	Not Attaining	70.7	1.4
AN0191	18	CPMI	6.00	Fair	Not Attaining	77.7	1.3
AN0661	18	CPMI	12.00	Good	Attaining	64.9	0.8
AN0662	18	CPMI	6.00	Fair	Not Attaining	68.9	0.7
AN0658	18	CPMI	14.00	Good	Attaining	65.9	5.2
AN0657	18	CPMI	6.00	Fair	Not Attaining	65.9	5.2
AN0656	18	CPMI	6.00	Fair	Not Attaining	65.9	5.2
AN0666	18	CPMI	6.00	Fair	Not Attaining	86.1	0.0
AN0654	18	CPMI	4.00	Poor	Not Attaining	92.9	0.0
AN0668	18	CPMI	10.00	Fair	Not Attaining	69.5	11.6
AN0669	18	CPMI	8.00	Fair	Not Attaining	65.0	10.9
AN0670	18	CPMI	8.00	Fair	Not Attaining	58.5	17.0
AN0673	18	CPMI	10.00	Fair	Not Attaining	27.3	40.7
AN0674	18	CPMI	8.00	Fair	Not Attaining	27.3	40.7
AN0675	18	CPMI	8.00	Fair	Not Attaining	26.4	46.0
AN0676	18	CPMI	8.00	Fair	Not Attaining	14.0	61.2

SITE	WMA	Macro Index	SCORE	Quality	Regulatory Status	Percent Urban	Percent Ag Land
AN0677	18	CPMI	6.00	Fair	Not Attaining	14.0	61.2
AN0678	18	CPMI	8.00	Fair	Not Attaining	15.0	54.7
AN0679	18	CPMI	10.00	Fair	Not Attaining	18.8	43.4
AN0680	18	CPMI	10.00	Fair	Not Attaining	23.8	44.8
AN0682	18	CPMI	12.00	Good	Attaining	23.5	42.0
AN0681	18	CPMI	22.00	Excellent	Attaining	23.5	42.0
AN0683	18	CPMI	14.00	Good	Attaining	25.0	44.0
AN0686	18	CPMI	28.00	Excellent	Attaining	10.9	48.9
AN0687	18	CPMI	14.00	Good	Attaining	12.3	48.8
AN0688	18	CPMI	4.00	Poor	Not Attaining	16.5	50.2
AN0690	17	CPMI	4.00	Poor	Not Attaining	9.8	67.0
AN0692	17	CPMI	12.00	Good	Attaining	8.9	59.5
AN0691	17	CPMI	0.00	Poor	Not Attaining	14.2	63.9
AN0694	17	CPMI	4.00	Poor	Not Attaining	12.6	65.7
AN0693	17	CPMI	8.00	Fair	Not Attaining	12.6	65.7
AN0696	17	CPMI	2.00	Poor	Not Attaining	9.7	52.2
AN0695	17	CPMI	8.00	Fair	Not Attaining	9.7	52.2
AN0697	17	CPMI	8.00	Fair	Not Attaining	5.6	57.0
AN0698	17	CPMI	6.00	Fair	Not Attaining	5.6	57.0
AN0700	17	CPMI	18.00	Good	Attaining	8.0	63.8
AN0699	17	CPMI	6.00	Fair	Not Attaining	7.6	57.2
AN0701	17	CPMI	16.00	Good	Attaining	12.7	22.6
AN0705	17	CPMI	16.00	Good	Attaining	11.9	48.1
AN0708	17	CPMI	4.00	Poor	Not Attaining	5.6	49.9
AN0709	17	CPMI	24.00	Excellent	Attaining	6.0	71.2
AN0710	17	CPMI	6.00	Fair	Not Attaining	6.6	73.8
AN0711	17	CPMI	8.00	Fair	Not Attaining	17.2	58.8
AN0712	17	CPMI	8.00	Fair	Not Attaining	8.3	71.6
AN0713	17	CPMI	4.00	Poor	Not Attaining	18.9	73.3
AN0714	17	CPMI	8.00	Fair	Not Attaining	18.9	73.3
AN0716	17	CPMI	6.00	Fair	Not Attaining	18.7	59.8
AN0717	17	CPMI	6.00	Fair	Not Attaining	5.7	56.1
AN0728	17	CPMI	20.00	Good	Attaining	29.7	16.0
AN0727	17	CPMI	12.00	Good	Attaining	29.7	16.0
AN0729	17	CPMI	8.00	Fair	Not Attaining	25.1	32.7
AN0731	17	CPMI	10.00	Fair	Not Attaining	10.4	46.4
AN0732	17	CPMI	8.00	Fair	Not Attaining	23.6	26.4
AN0730	17	CPMI	6.00	Fair	Not Attaining	23.6	26.4

SITE	WMA	Macro Index	SCORE	Quality	Regulatory Status	Percent Urban	Percent Ag Land
AN0721	17	PMI	56.13	Good	Attaining	40.1	12.9
AN0722	17	PMI	24.76	Poor	Not Attaining	35.2	10.6
AN0723	17	PMI	55.04	Fair	Not Attaining	35.2	10.6
AN0724	17	PMI	52.25	Fair	Not Attaining	18.0	9.9
AN0725	17	PMI	42.33	Fair	Not Attaining	28.9	13.5
AN0733	17	CPMI	10.00	Fair	Not Attaining	25.2	21.8
AN0735	17	CPMI	20.00	Good	Attaining	33.4	23.1
AN0734	17	PMI	54.72	Fair	Not Attaining	33.4	23.1
AN0736	17	CPMI	12.00	Good	Attaining	14.9	28.2
AN0737	17	CPMI	24.00	Excellent	Attaining	14.9	28.2
AN0738	17	PMI	36.41	Fair	Not Attaining	33.8	33.1
AN0739	17	CPMI	20.00	Good	Attaining	36.7	25.6
AN0740	17	CPMI	18.00	Good	Attaining	24.9	29.0
AN0750	17	CPMI	2.00	Poor	Not Attaining	63.5	10.1
AN0742	17	CPMI	4.00	Poor	Not Attaining	9.9	51.7
AN0741	17	CPMI	12.00	Good	Attaining	9.9	51.7
AN0745	17	CPMI	10.00	Fair	Not Attaining	12.5	49.6
AN0743	17	CPMI	8.00	Fair	Not Attaining	5.5	63.2
AN0744	17	CPMI	6.00	Fair	Not Attaining	5.5	63.2
AN0746	17	CPMI	4.00	Poor	Not Attaining	4.0	68.1
AN0747	17	CPMI	6.00	Fair	Not Attaining	4.0	68.1
AN0748	17	CPMI	10.00	Fair	Not Attaining	12.7	48.5
AN0749	17	CPMI	22.00	Excellent	Attaining	13.8	47.1
AN0752	17	CPMI	24.00	Excellent	Attaining	12.4	48.1
AN0751	17	CPMI	4.00	Poor	Not Attaining	23.9	28.9
AN0753	17	CPMI	14.00	Good	Attaining	13.5	36.1
AN0754	17	CPMI	4.00	Poor	Not Attaining	20.2	26.2
AN0756	17	CPMI	14.00	Good	Attaining	12.3	8.9
AN0758	17	PMI	53.39	Fair	Not Attaining	21.9	47.7
AN0757	17	PMI	36.60	Fair	Not Attaining	37.5	36.2
AN0759	17	PMI	47.96	Fair	Not Attaining	29.8	36.6
AN0761	17	PMI	67.60	Excellent	Attaining	25.6	21.3
AN0760	17	PMI	64.78	Excellent	Attaining	25.0	25.6
AN0762	17	PMI	69.55	Excellent	Attaining	7.9	16.9
AN0763	17	PMI	57.73	Good	Attaining	6.5	6.4
AN0765	16	PMI	59.21	Good	Attaining	3.0	1.5
AN0766	16	PMI	68.47	Excellent	Attaining	7.4	7.4
AN0769	16	PMI	49.34	Fair	Not Attaining	11.0	4.6

SITE	WMA	Macro Index	SCORE	Quality	Regulatory Status	Percent Urban	Percent Ag Land
AN0771	16	CPMI	8.00	Fair	Not Attaining	27.8	3.7
AN0499	13	CPMI	4.00	Poor	Not Attaining	16.2	6.8
AN0500	13	CPMI	14.00	Good	Attaining	16.2	6.8
AN0501	13	CPMI	24.00	Excellent	Attaining	39.0	5.2
AN0503	13	CPMI	6.00	Fair	Not Attaining	45.6	4.4
AN0504	13	CPMI	24.00	Excellent	Attaining	45.6	4.4
AN0505	13	CPMI	24.00	Excellent	Attaining	38.5	7.0
AN0502	13	CPMI	18.00	Good	Attaining	43.3	5.2
AN0506	13	CPMI	16.00	Good	Attaining	43.3	5.2
AN0507	13	CPMI	16.00	Good	Attaining	43.3	5.2
AN0508	13	CPMI	24.00	Excellent	Attaining	7.8	5.7
AN0509	13	PMI	36.59	Fair	Not Attaining	16.8	4.2
AN0510A	13	PMI	29.12	Poor	Not Attaining	26.3	4.8
AN0510	13	PMI	30.15	Poor	Not Attaining	35.9	3.6
AN0512	13	CPMI	16.00	Good	Attaining	38.4	3.1
AN0511	13	PMI	37.39	Fair	Not Attaining	38.4	3.1
AN0513	13	CPMI	6.00	Fair	Not Attaining	80.7	0.0
AN0514	13	CPMI	4.00	Poor	Not Attaining	43.1	3.9
AN0515	13	CPMI	6.00	Fair	Not Attaining	59.1	0.7
AN0519A	13	CPMI	12.00	Good	Attaining	27.7	7.9
AN0517	13	CPMI	8.00	Fair	Not Attaining	27.7	7.9
AN0518	13	CPMI	8.00	Fair	Not Attaining	27.7	7.9
AN0519	13	PMI	57.76	Good	Attaining	26.4	4.0
AN0520	13	PMI	50.84	Fair	Not Attaining	27.2	4.0
AN0521	13	PMI	64.56	Excellent	Attaining	4.8	2.1
AN0522	13	PMI	68.29	Excellent	Attaining	35.8	3.9
AN0523	13	PMI	66.11	Excellent	Attaining	29.4	3.5
AN0524	13	CPMI	26.00	Excellent	Attaining	26.8	2.7
AN0525A	13	PMI	38.08	Fair	Not Attaining	9.3	4.6
AN0526	13	PMI	37.63	Fair	Not Attaining	9.3	4.6
AN0527	13	PMI	70.74	Excellent	Attaining	14.1	3.1
AN0528	13	PMI	70.91	Excellent	Attaining	17.9	3.1
AN0529	13	PMI	70.24	Excellent	Attaining	7.9	1.4
AN0531	13	PMI	68.15	Excellent	Attaining	8.8	1.1
AN0532	13	PMI	43.08	Fair	Not Attaining	45.8	0.8
AN0533	13	PMI	59.86	Good	Attaining	21.3	2.0
AN0530	13	PMI	59.11	Good	Attaining	21.3	2.0
AN0534	13	PMI	51.37	Fair	Not Attaining	21.3	2.0

SITE	WMA	Macro Index	SCORE	Quality	Regulatory Status	Percent Urban	Percent Ag Land
AN0536	13	PMI	76.25	Excellent	Attaining	6.9	0.0
AN0540	13	PMI	47.91	Fair	Not Attaining	26.0	0.4
AN0541	13	PMI	61.24	Good	Attaining	33.8	0.2
AN0537	13	PMI	62.12	Good	Attaining	33.8	0.1
AN0539	13	PMI	50.64	Fair	Not Attaining	33.8	0.1
AN0538	13	PMI	49.97	Fair	Not Attaining	33.8	0.1
AN0535	13	PMI	67.89	Excellent	Attaining	27.9	2.6
AN0542	13	PMI	58.69	Good	Attaining	14.2	0.1
AN0543	13	PMI	52.77	Fair	Not Attaining	14.2	0.1
AN0544	13	PMI	46.31	Fair	Not Attaining	76.8	2.0
AN0545	13	PMI	44.33	Fair	Not Attaining	0.4	0.0
AN0546	13	PMI	60.87	Good	Attaining	2.9	0.0
AN0547	13	PMI	68.87	Excellent	Attaining	4.4	0.7
AN0548	13	PMI	64.17	Excellent	Attaining	4.5	0.3
AN0549	13	PMI	63.06	Excellent	Attaining	9.3	0.3
AN0550	13	PMI	63.61	Excellent	Attaining	0.8	0.0
AN0551	13	PMI	68.09	Excellent	Attaining	13.0	0.0
AN0552	13	PMI	77.75	Excellent	Attaining	7.4	0.2
AN0554	13	PMI	20.39	Poor	Not Attaining	33.6	0.7
AN0555A	13	PMI	66.57	Excellent	Attaining	23.8	0.0
AN0555	13	PMI	23.95	Poor	Not Attaining	30.3	0.3
AN0556	13	PMI	44.83	Fair	Not Attaining	10.4	0.1
AN0557A	13	PMI	71.96	Excellent	Attaining	0.4	0.1
AN0557	13	PMI	60.71	Good	Attaining	6.2	0.5
AN0559A	13	PMI	59.07	Good	Attaining	0.4	0.1
AN0559	13	PMI	54.05	Fair	Not Attaining	5.2	0.0
AN0580	14	PMI	61.98	Good	Attaining	0.4	0.7
AN0581	14	PMI	64.17	Excellent	Attaining	0.4	0.7
AN0582	14	PMI	31.31	Poor	Not Attaining	26.7	29.4
AN0583	14	PMI	46.14	Fair	Not Attaining	26.7	29.4
AN0585	14	PMI	51.86	Fair	Not Attaining	17.2	18.8
AN0584	14	PMI	43.83	Fair	Not Attaining	17.2	18.8
AN0579	14	PMI	59.85	Good	Attaining	2.3	7.9
AN0586A	14	PMI	69.88	Excellent	Attaining	2.3	7.9
AN0587	14	PMI	67.49	Excellent	Attaining	0.1	0.0
AN0586	14	PMI	51.92	Fair	Not Attaining	6.4	8.9
AN0560	14	PMI	35.88	Fair	Not Attaining	16.5	3.6
AN0562	14	PMI	61.76	Good	Attaining	11.6	2.7

SITE	WMA	Macro Index	SCORE	Quality	Regulatory Status	Percent Urban	Percent Ag Land
AN0561	14	PMI	54.90	Fair	Not Attaining	11.6	2.7
AN0563	14	PMI	54.82	Fair	Not Attaining	8.7	18.8
AN0565	14	PMI	56.35	Good	Attaining	42.6	8.9
AN0566	14	PMI	70.92	Excellent	Attaining	24.0	7.4
AN0569	14	PMI	32.88	Poor	Not Attaining	25.0	21.5
AN0568	14	PMI	39.55	Fair	Not Attaining	16.0	22.3
AN0567	14	PMI	64.17	Excellent	Attaining	16.0	22.3
AN0570	14	PMI	28.90	Poor	Not Attaining	26.8	31.9
AN0571	14	PMI	50.88	Fair	Not Attaining	21.8	24.2
AN0572	14	PMI	68.44	Excellent	Attaining	21.8	24.2
AN0573	14	PMI	38.86	Fair	Not Attaining	15.8	47.7
AN0574	14	PMI	57.99	Good	Attaining	22.4	36.7
AN0575	14	PMI	44.33	Fair	Not Attaining	22.4	36.7
AN0564	14	PMI	73.37	Excellent	Attaining	8.0	4.4
AN0577	14	PMI	32.28	Poor	Not Attaining	27.0	34.4
AN0578	14	PMI	56.64	Good	Attaining	14.5	19.3
AN0593	14	PMI	61.28	Good	Attaining	12.7	8.7
AN0590	14	PMI	54.72	Fair	Not Attaining	17.0	4.7
AN0591	14	PMI	62.78	Good	Attaining	18.9	12.8
AN0594	14	PMI	55.02	Fair	Not Attaining	13.0	9.4
AN0592	14	PMI	72.90	Excellent	Attaining	13.0	9.4
AN0603	14	PMI	66.79	Excellent	Attaining	1.5	0.0
AN0604	14	PMI	69.81	Excellent	Attaining	1.9	0.1
AN0605	14	PMI	70.11	Excellent	Attaining	0.0	0.0
AN0606	14	PMI	52.08	Fair	Not Attaining	1.9	0.3
AN0607	14	PMI	64.17	Excellent	Attaining	1.8	0.5
AN0595	14	PMI	54.81	Fair	Not Attaining	3.3	2.0
AN0596	14	PMI	51.80	Fair	Not Attaining	2.7	2.9
AN0597	14	PMI	52.01	Fair	Not Attaining	0.5	0.4
AN0597A	14	PMI	68.06	Excellent	Attaining	0.5	0.4
AN0601	14	PMI	46.64	Fair	Not Attaining	1.1	1.2
AN0599	14	PMI	58.41	Good	Attaining	0.1	0.0
AN0600	14	PMI	45.33	Fair	Not Attaining	0.1	0.0
AN0602	14	PMI	57.73	Good	Attaining	1.2	1.2
AN0610	14	PMI	65.21	Excellent	Attaining	0.7	0.1
AN0612	14	PMI	62.92	Good	Attaining	2.9	0.0
AN0611	14	PMI	63.17	Excellent	Attaining	2.9	0.0
AN0613	14	PMI	59.07	Good	Attaining	15.4	16.3

SITE	WMA	Macro Index	SCORE	Quality	Regulatory Status	Percent Urban	Percent Ag Land
AN0614	14	PMI	59.08	Good	Attaining	19.5	9.1
AN0615	14	PMI	50.16	Fair	Not Attaining	32.7	0.8
AN0616	15	PMI	43.13	Fair	Not Attaining	56.6	0.0
AN0617	15	PMI	60.96	Good	Attaining	44.7	0.2
AN0621	15	PMI	61.07	Good	Attaining	47.7	6.6
AN0620	15	PMI	42.48	Fair	Not Attaining	47.7	6.6
AN0622	15	PMI	59.29	Good	Attaining	48.5	8.6
AN0623	15	PMI	75.47	Excellent	Attaining	39.9	7.5
AN0624	15	PMI	42.90	Fair	Not Attaining	36.4	11.6
AN0626	15	PMI	71.62	Excellent	Attaining	18.2	32.3
AN0625	15	PMI	78.36	Excellent	Attaining	30.1	11.3
AN0627	15	PMI	46.03	Fair	Not Attaining	27.5	25.4
AN0628	15	PMI	19.83	Poor	Not Attaining	28.3	21.5
AN0629	15	PMI	60.02	Good	Attaining	11.6	6.5
AN0630	15	PMI	60.90	Good	Attaining	12.7	7.8
AN0631	15	PMI	21.23	Poor	Not Attaining	10.1	25.5
AN0632	15	PMI	43.03	Fair	Not Attaining	10.1	25.5
AN0634	15	PMI	58.33	Good	Attaining	10.6	1.6
AN0633	15	PMI	59.64	Good	Attaining	16.5	15.7
AN0635	15	PMI	71.75	Excellent	Attaining	22.1	12.4
AN0636	15	PMI	33.60	Poor	Not Attaining	10.7	7.9
AN0637	15	PMI	77.25	Excellent	Attaining	10.7	7.9
AN0638	15	PMI	68.63	Excellent	Attaining	18.8	10.6
AN0639	15	PMI	61.91	Good	Attaining	10.4	4.1
AN0640B	15	PMI	55.98	Fair	Not Attaining	14.6	5.6
AN0640	15	PMI	69.44	Excellent	Attaining	14.6	5.6
AN0640A	15	PMI	67.07	Excellent	Attaining	14.6	5.6
AN0643	15	PMI	72.83	Excellent	Attaining	10.9	10.0
AN0644	15	PMI	51.17	Fair	Not Attaining	10.2	6.2
AN0642	15	PMI	63.97	Excellent	Attaining	21.8	1.1
AN0646	15	PMI	38.79	Fair	Not Attaining	9.4	2.2
AN0645	15	PMI	66.20	Excellent	Attaining	9.4	2.2
AN0647	15	PMI	64.49	Excellent	Attaining	4.3	1.8
AN0618	15	PMI	49.36	Fair	Not Attaining	36.4	1.5
AN0619	15	PMI	41.98	Fair	Not Attaining	36.4	2.5
AN0648	15	PMI	56.32	Good	Attaining	10.3	6.0
AN0651	15	PMI	58.52	Good	Attaining	6.2	0.7
AN0649	15	PMI	68.04	Excellent	Attaining	4.4	4.5

SITE	WMA	Macro Index	SCORE	Quality	Regulatory Status	Percent Urban	Percent Ag Land
AN0652	15	PMI	46.51	Fair	Not Attaining	4.2	1.6
AN0650	15	PMI	55.46	Fair	Not Attaining	5.0	4.3

Appendix B Spatial Weight Matrix Connectivity Histograms

Figure B-1. 3-Mile distance weighted connectivity histogram.

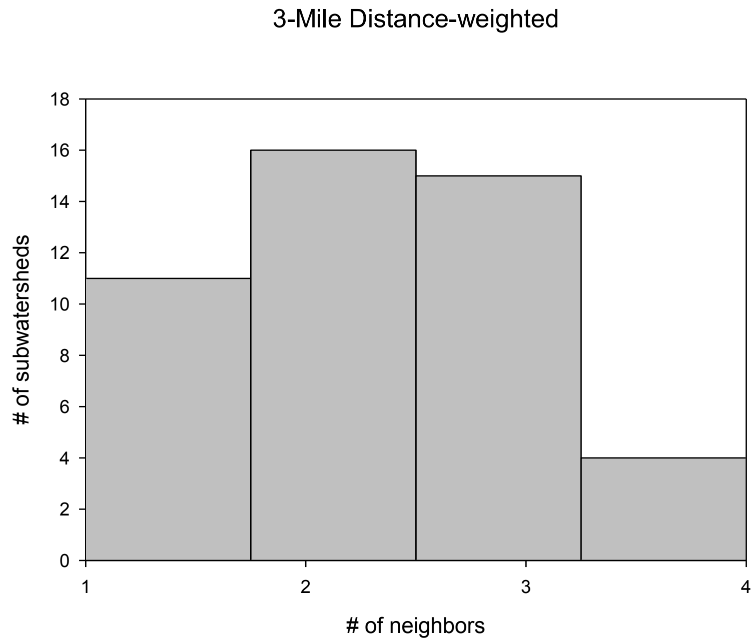


Figure B-2. 10-Mile distance weighted connectivity histogram.

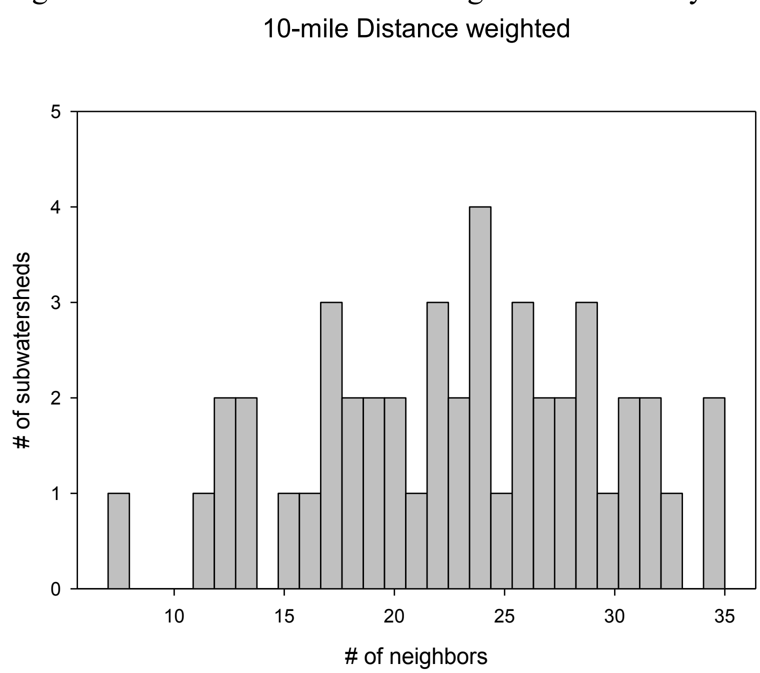


Figure B-3. Queen contiguity connectivity histogram.

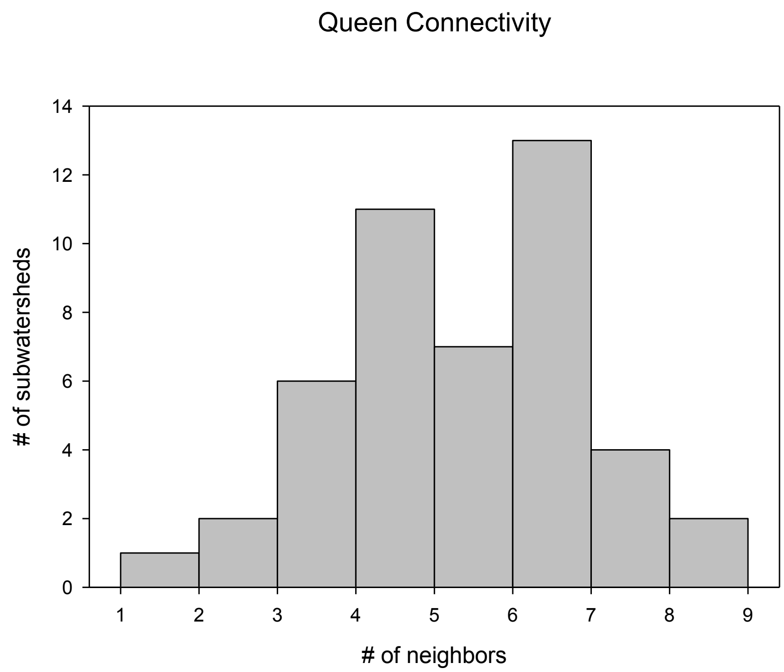


Figure B-4. Queen 2nd-order pure continguity connectivity histogram.

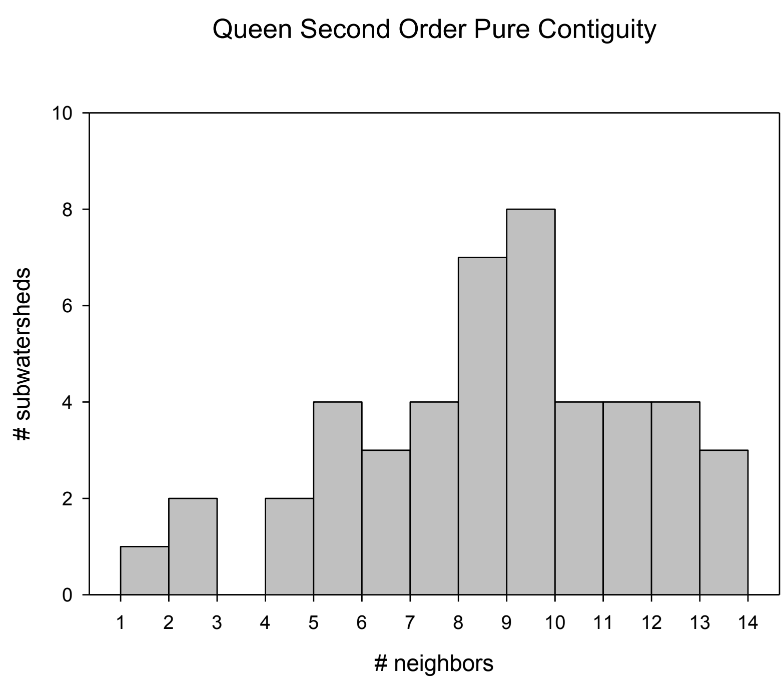
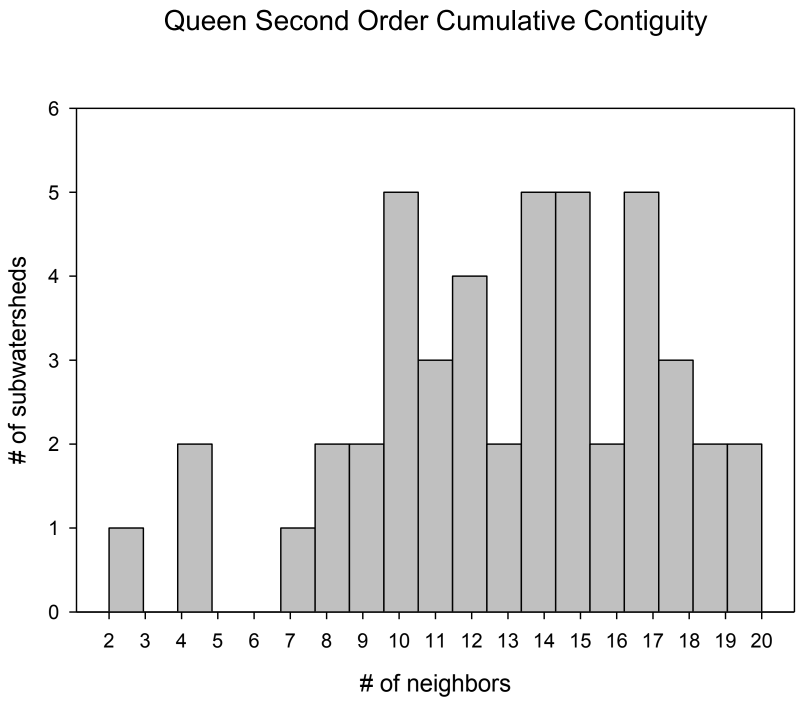


Figure B-5. Queen 2nd-order cumulative contiguity connectivity histogram.



Appendix C LISA Significance and Cluster Maps

Figure C-1a. LISA significance map for probability of impairment for subwatersheds of WMA 6.

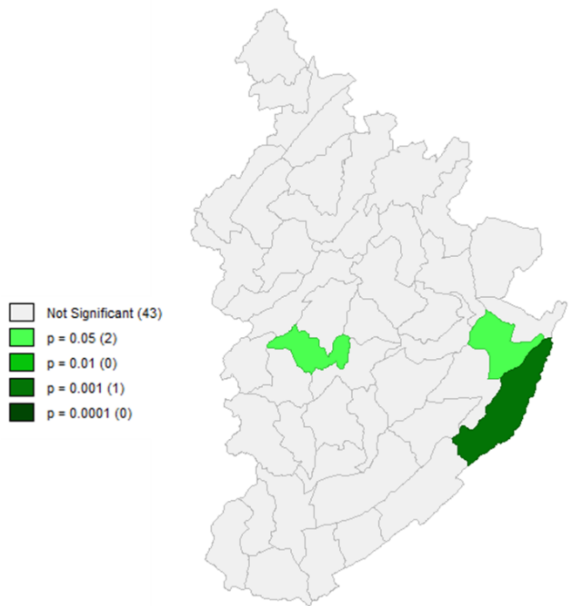


Figure C-1b. LISA cluster map for probability of impairment for subwatersheds of WMA 6.

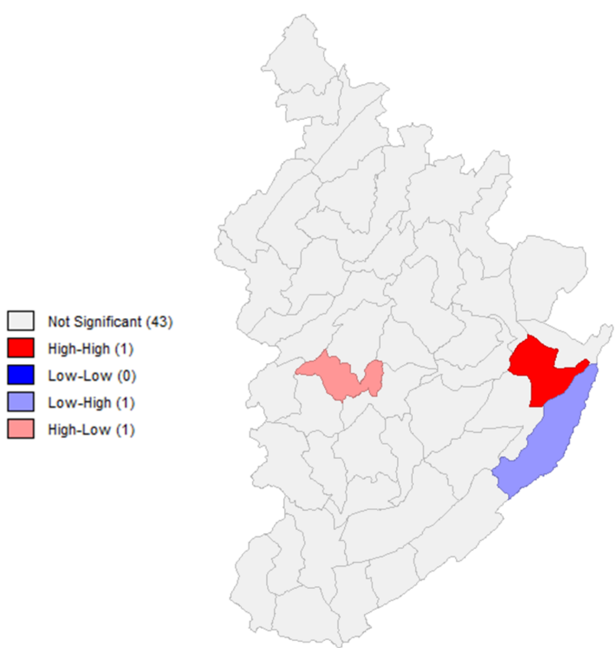


Figure C-2a. LISA significance map for cumulative drainage area for subwatersheds of WMA 6.

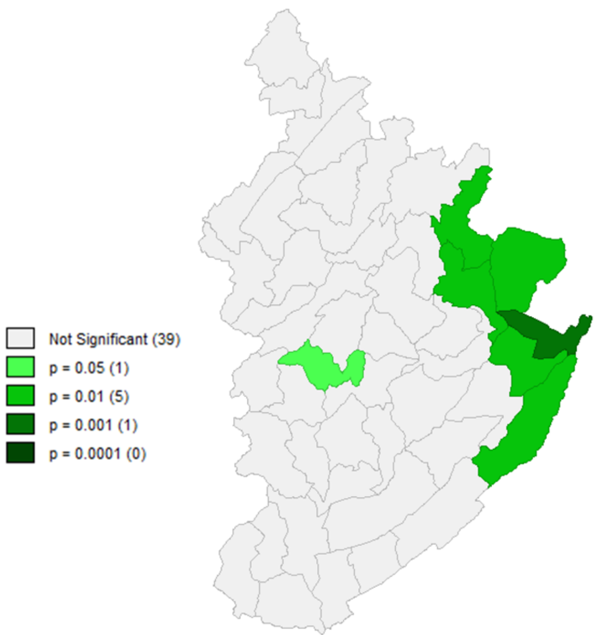


Figure C-2b. LISA cluster map for cumulative drainage area for subwatersheds of WMA 6.

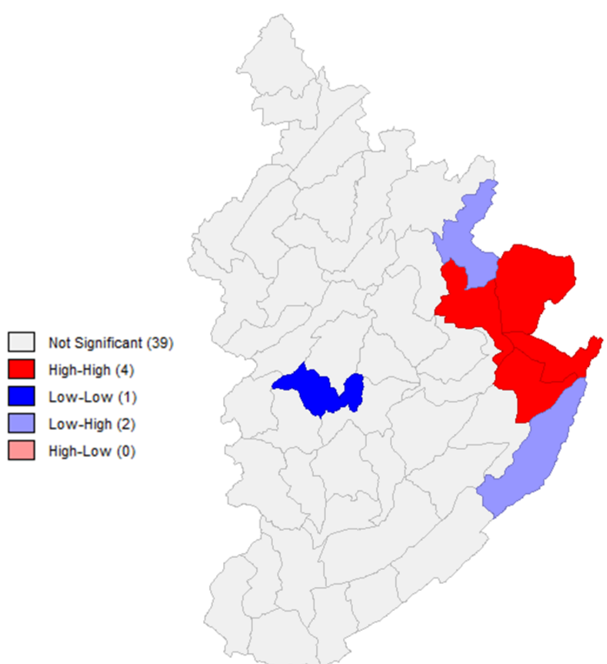


Figure C-3a. LISA significance map for proportion agricultural LULC for subwatersheds of WMA 6.

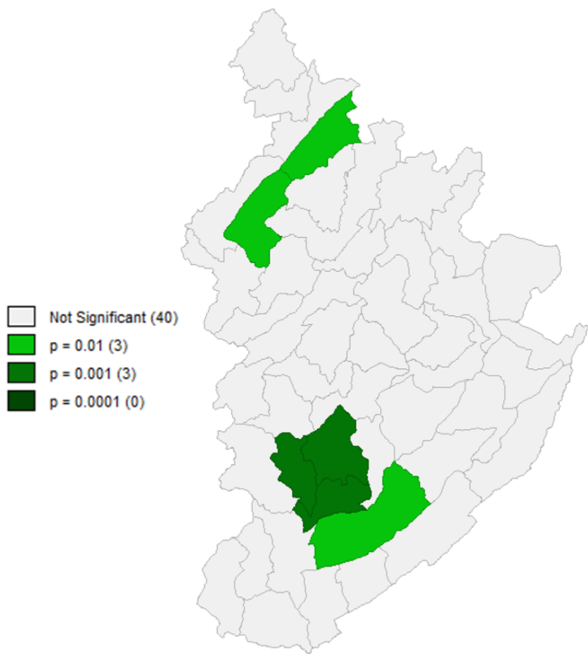


Figure C-3b. LISA cluster map for proportion agricultural LULC for subwatersheds of WMA 6.

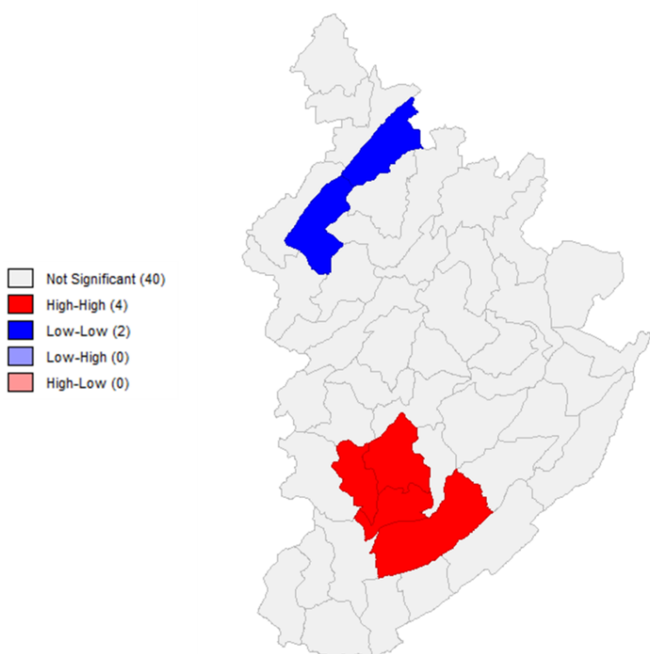


Figure C-4a. LISA significance map for proportion impervious cover for subwatersheds of WMA 6.

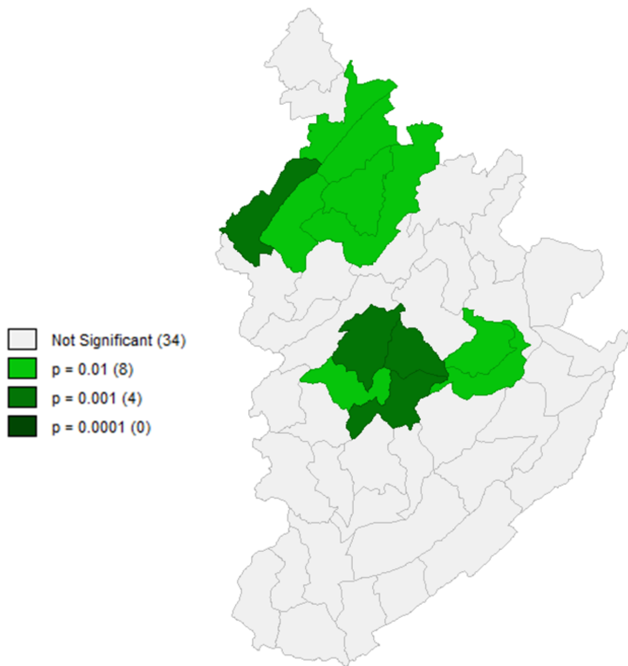


Figure C-4b. LISA cluster map for proportion impervious cover for subwatersheds of WMA 6.

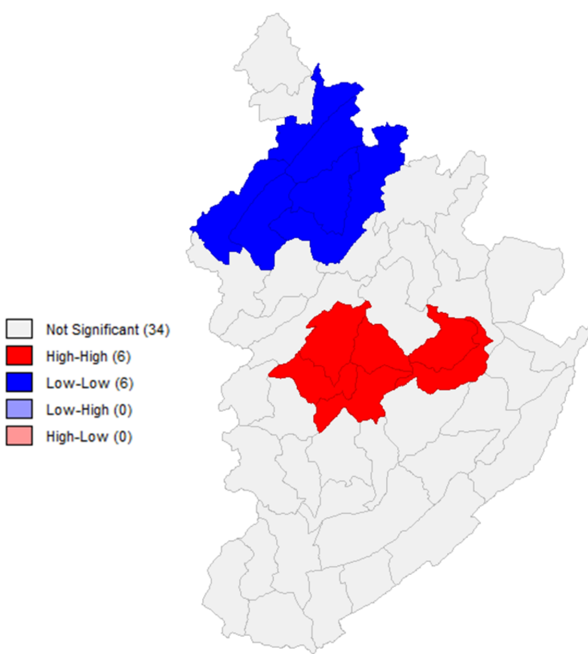


Figure C-5a. LISA significance map for U_N (x100) for subwatersheds of WMA 6.

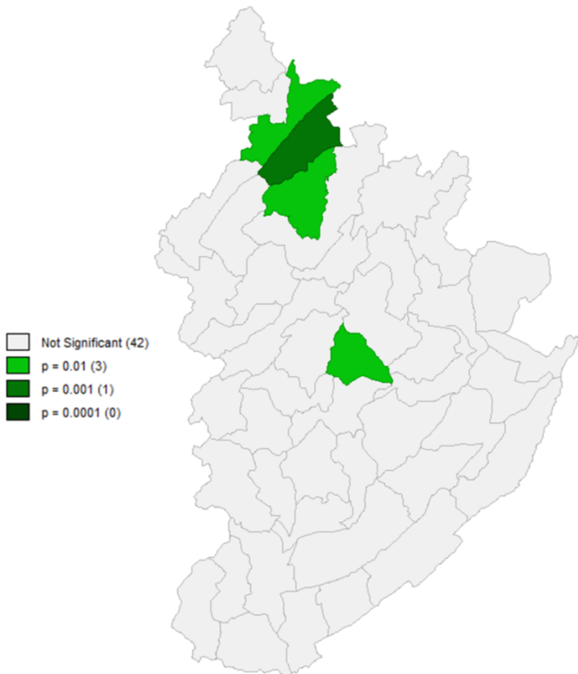
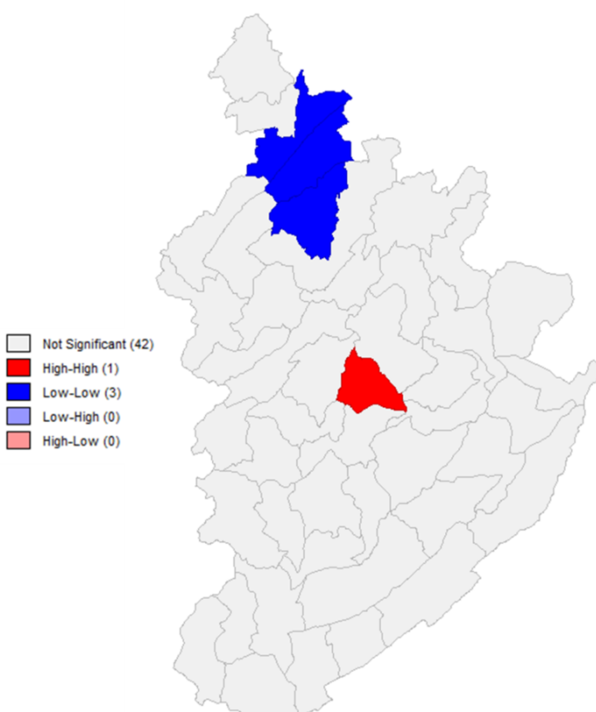


Figure C-5b. LISA cluster map for U_N (x100) for subwatersheds of WMA 6.



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